SOLVENT SUBSTITUTION METHODOLOGY USING MULTIATTRIBUTE UTILITY THEORY AND THE ANALYTICAL HIERARCHICAL PROCESS

THESIS

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Preface

The objective of this research is to develop a multicriteria decision making methodology for the ranking of solvent objectives. This includes development of univariate value functions and criteria and the incorporation of required alternative attributes. Research results are limited to Air Force cleaning process efforts and do not address policy or planning objectives. Changing the attributes and criteria could alter the applicability of the developed process although the general methodology will still apply.

Many individuals deserve thanks for helping me with this effort. I would like to thank my thesis advisor Dr. Yupo Chan and my reader Dr. Charles Bleckmann for their support and encouragement. I also thank Capt. Alan Butler and the members of the Solvent "Expert Team" for their help in developing the decision models. Finally, I wish to thank my wife Melissa, son Nicholas, and daughter Chelsea for their patience, understanding and support.

Jaimie S. Tiley

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Abstract

This study developed a multicriteria decision making methodology for the ranking of solvent cleaning process alternatives. This includes development of univariate value functions and criteria and the incorporation of required alternative attributes provided through solvent characterization. It also compares Multiattribute Utility Theory (MAUT) and the Analytical Hierarchical Process (AHP) in reference to the cleaning process evaluation problem. An actual Air Force cleaning process evaluation problem is considered to verify the research. The test problem ranks several cleaning alternatives for the replacement of a hazardous solvent used in the general cleaning of aircraft engine components.

Factors are identified which impact wipe solvent substitution decisions. The factors provide minimum test requirements for alternative comparisons. Although both MAUT and AHP provided decision models for ranking the alternatives, there were problems associated with using either method including independence constraints and scaling issues. Additionally, the Decision Maker had difficulty with the use of the nine point scale in AHP and the calculation of MAUT univariate utility functions using lottery techniques. The research identified the need for stringent criteria clarification prior to establishing univariate functions.

Additional research is required to identify specific test methods for quantifying the established criteria factors and to investigate the integration of MAUT and AHP into viable decision tool.

Chapter 1

Introduction

Background

Manufacturing and maintenance processes use solvents in a variety of applications. The solvents are typically chosen based on many factors, including previous engineering practices and operational costs. With new environmental regulations and restrictions on the use of hazardous materials, it is becoming difficult and expensive to use solvents which meet hazardous material characteristics established by the Resource Conservation and Recovery Act (RCRA) and the Comprehensive Environmental Compensation and Liability Act (CERCLA). In addition, new Clean Air Act (CAA), Clean Water Act (CWA) and National Pollutant Discharge Elimination System (NPDES) requirements concerning air emissions, storm water runoff, and industrial point source discharges are increasing pressure to reduce hazardous solvent use. Several of the most common cleaning solvents are classified as class I ozone depleting substances (ODS) under the Montreal Protocol which mandates their elimination from Air Force (AF) processes. Furthermore, the National Defense Authorization Act of 1993 forbids contract awards after June 1, 1993 that contain technical specifications for ODS or set requirements that may be met only through the use of ODS without an approved policy waiver.

Air Force uses of hazardous solvents are typically at Air Logistics Centers in the parts cleaning and paint stripping areas. Significant amounts of hazardous solvents are also used by field personnel for equipment maintenance. In most cases, the specific chemicals are referenced by technical data which may be connected to equipment warranties and liability issues. Unfortunately, technical instructions were typically copied in large part from existing documentation for similar processes. As a result,

documentation has become layered with multiple cross references. Changing a particular specification or reference is complicated by affected technical documents making it difficult to determine change impacts without intensive data searches. Given there are currently 175,000 technical orders (TOs), military specification and standards and many of their consumable substances used are referenced by specification numbers, it is difficult to determine where hazardous solvents and ODS are used in maintenance processes. An investigation of these documents revealed there are over 230 AF prepared documents indirectly calling for the use of chlorofluorocarbons, over 181 documents indirectly calling for the use of halons, and over 225 documents indirectly calling for the use of chlorinated solvents in the production , operation and maintenance of weapon systems (1:2,3).

The cleaning solvent 1,1,1 trichloroethane (TCA) is one of the most widely used ODS in the maintenance of aircraft engines. Typically, engine processes use TCA as a wipe cleaner prior to chemical surface coating, epoxy applications for threaded inserts and general cleaning of fuel pumps. TCA is also used in the vapor degreasing of engine accessory components. P-D-680 type II (Stoddard Solvent) is another hazardous material that is heavily use in engine processes. A recent analysis of TOs for a new fighter engine found 6 TOs with 9 work packages directly specifying the use of TCA and 17 TOs with 76 work packages specifying the use of P-D-680 type II.

With passage of the Federal Facility Compliance Act, bases are now liable for environmental fines and penalties associated with RCRA violations. As a result, AF bases are aggressively seeking replacements for many hazardous materials. The engine maintenance facilities at these bases are increasingly requesting approval to use environmentally safe alternative solvents. Although many potential substitutes exist for ODS and hazardous materials, solvents must be carefully matched to specific applications.

In some cases, processes must be modified for alternatives to work. Altering the processes which use the hazardous chemicals is complicated by strict requirements for material and process compatibility's. For example, a process which uses a hazardous solvent for a particular cleaning task may be part of a multi-stage refurbishment effort involving many specific tasks. Altering a specific process chemical at one stage may have drastic effects on subsequent stages.

Many solvent manufacturers are offering replacements for common hazardous chemicals which have dramatically different efficiencies, chemical properties, costs, and environmental and human health impacts. Given the variability of alternative attributes, it is difficult to effectively rank replacement alternatives. In addition, many of the factors that must be considered involve parameters such as risk and future liabilities which are difficult to quantify as cardinal values (that is, values with numbers associated with it).

These problems make it difficult to defend specific choices and justify funds allocations for replacement efforts against competing projects. Many of the current decisions to use replacements are based on similarity of processes. For example, consider landing gear bearing journals cleaned with chemical A in shop 1. When shop 2 needs a replacement chemical to clean engine bearing journals, they consider chemical A. The problem associated with this approach, especially with engine processes, is that slight material incompatibilities lead to component degradation which is devastating to system functions. There currently is no process which addresses these factors and provides a justifiable ranking methodology for scoring solvent alternatives.

The use of multicriteria decision making (MCDM) techniques have been widely used by industry to resolve similar problems involving multiple attributes and criteria. In particular, Multiattribute Utility Theory (MAUT) provides a potential methodology for solving this particular problem. The theory allows decision makers to rank or prioritize potential options (called alternatives) and characterize preferences for complex problems

involving multiple objectives. The decision options may involve many attributes and characteristics which impact the ranking. Unfortunately, the MAUT process is very rigorous and sometimes difficult to implement as a specific problem technique, requiring development of utility functions, attribute pairwise comparisons, and establishment of preferences.

The Analytical Hierarchical Process (AHP) is a type of MAUT technique which simplifies the process by applying several assumptions to the problem. If applicable, the AHP process provides a simpler problem methodology which is far easier to implement in field applications. As with most systems, there are strengths and weaknesses associated with the two techniques. Combining the processes may provide an efficient model for field application. This research will develop a methodology to meet the field level requirement for a solvent alternative ranking management decision tool.

Research Problem

Environmental and financial pressures mandate replacement of hazardous solvents in maintenance and repair processes and the evaluation of cleaning processes prior to their authorization. Current cost benefit tools used to justify replacements do not effectively address the multivariate criteria and attributes which impact the decision process. A methodology to allow comparisons of cleaning alternatives and address criteria is needed. The methodology must account for dependence of alternative attributes, preferences of decision makers and allow verification of results/process. In addition, the methodology must be easily used and understood by the decision makers, providing accurate results which are defensible.

Research Objective

The purpose of this research is to develop a multicriteria decision making methodology for the ranking of solvent cleaning process alternatives. The methodology will specify required attribute data, criteria and value functions involved and provide a format for determining preferences using applicable survey techniques. This includes development of univariate value functions and criteria and the incorporation of them into a multivariate utility function. It also includes identification of required alternative attributes provided through solvent characterization. Applicable software programs will be considered in the process. In addition, the research will compare MAUT and AHP techniques in reference to the cleaning process evaluation problem. An actual Air Force cleaning process evaluation problem will be used to verify the research. The problem will rank several cleaning alternatives for the replacement of hazardous solvents used in the general cleaning of aircraft engine components.

Research Scope and Limitations

This research concerns the cleaning process selection problem in reference to maintenance and repair processes associated with aircraft engines. The research is limited to Air Force cleaning process efforts and does not address policy or planning objectives. The resulting methodology is applicable to process selection problems involving the given problem criteria and general alternative attributes. Changing attributes and criteria could alter the applicability of the developed process although the general methodology will apply as long as dependence requirements are maintained.

Organization of the Report

The first step in this research will characterize the problem and establish the MAUT foundation through a literature review and data query of solvent cleaning process characteristics. Following the review, the overall MAUT methodology will be developed, including the identification of attributes, scaling univariate value functions, establishing the multivariate utility functions and developing the verification process. The AHP process will also be addressed in reference to applicability and adaptation to the replacement problem. Dependence constraints, rank reversal and strategic equivalence between AHP and MAUT processes will also be discussed. The methodologies will be analyzed using the test cleaning process problem with results reported in Chapter 4. Chapter 5 will include the conclusions of the research and recommendations for future study.

Chapter 2
Literature Review/Background

The purpose of this review is to determine the methods currently used to evaluate cleaning processes and identify pertinent criteria and attributes. Government processes at ASC, depot and field level will be characterized. Since the engine contractors are also required to make similar cleaning process decisions, their methods will be included in the research. For purposes of this effort, the contractor list will include Pratt & Whitney, General Electric and Allison (these contractors produce the majority of aircraft engines currently used by the AF) (1:2,3).

In addition, applications of multicriteria decision making techniques, Multiattribute Utility Theory (MAUT) and Analytical Hierarchical Process (AHP) in particular, are investigated. The advantages and disadvantages associated with the use of MAUT and AHP to resolve the cleaning process selection problem are researched and specified. The results of this review will be used to determine the methodology and management models developed in the next chapter.

Cleaning process evaluation occurs at two major phases in the process' life cycle. The first occurs during the design phase of a weapon system subsystem or component where processes are evaluated prior to specifying maintenance procedures. The second occurs when cleaning processes are substituted or modified after development/authorization. Although both evaluations involve similar constraints and criteria, the two cases have unique problems and considerations. Both cases are discussed below.

Current Design Process

In AF aircraft engine procurements, cleaning processes are identified early in the procurement effort as part of the system engineering process and logistic assessments. The statement of work (SOW) which defines contractor tasking typically requires the contractor to evaluate cleaning processes associated with the manufacturing and maintenance of the engine systems in accordance with the system engineering specification (2:1-5). These requirements include evaluation of critical materials and processes including cleaning solvents. The AF reviews the contractor's performance to the standard throughout the system procurement and conducts assessments to verify compliance. New changes to the military standard include development of an Industrial Process Environmental Assessment (IPEA) (3:1). The IPEA is used by the AF and contractors to identify and eliminate or minimize the use of hazardous materials in the life cycle of the engine system. The evaluation is actually a series of assessments conducted throughout the systems procurement which are intended to provide rationale for environmental decisions (IPEA data Item). Unfortunately, most AF engine systems currently in development or operation did not include IPEA requirements in their contracts and therefore did not address specific environmental issues under the systems engineering approach.

SOWs typically require logistic support analysis (LSA) in accordance with military standard 1388-2B. The purpose of LSA is to document design and support processes which were established through the system engineering process (4: 1-5). The LSA is divided into different elements within the system including engineering data on cleaning processes, solvents, tooling requirements and part listings. The information is reviewed during the procurement program and documented in a Logistic Support Analysis Record. Part of the LSAR is text material on maintenance procedures which, once accepted by the

AF, is used by technical writers to develop the maintenance technical orders (5:1). As part of the review, AF personnel including depot and field level personnel discuss the cleaning procedures and related chemicals and equipment. Environmental and safety concerns are addressed by evaluators to ensure compliance with AF goals. Although criteria are considered during the reviews, MCDM techniques are typically not applied to LSA reviews. The cleaning processes are usually recommended by contractors based upon existing procedures and experience. Alternatives are not ranked or even identified at this level. Only if the AF disapproves a process will the contractors change procedures and evaluate alternatives. Specific criteria and MCDM parameters are usually not considered.

Technical orders are written using AF approved LSA data. Once written, the AF and contractors validate and verify the documentation. This usually involves actual system equipment and AF maintenance personnel. Although the verification of the processes identifies specific process compatibility, effectiveness and related human health/safety impacts, it doesn't effectively address environmental issues since the goal of the effort is to verify the data accomplishes the maintenance task (6:1).

With concern over environmental issues increasing, the AF is developing a requirement on new contracts for contractors to develop hazardous material management plans and programs in accordance with National Aerospace Standard 411 (NAS 411). NAS 411 is an Aerospace Industries Standard applied to Department of Defense procurements. It establishes a hazardous materials management program (HMMP) with the intent to reduce hazardous materials involved in the system's life cycle (7:1). According to the document, "the HMMP is the contractor's plan to assure appropriate consideration is given to the elimination/reduction of hazardous materials, and to the proper control of hazardous materials that are not eliminated..." (7:1). Program activities and tasks are documented in a management plan which the contractor provides to the AF

as a deliverable data item (8:1). Although the program includes considerations for health and environmental risk evaluations (7:3), it allows the contractor freedom in evaluating potential processes. This standard and associated data items are currently being reviewed by AF acquisition officials.

Current Solvent Substitution Process

There are three main areas where solvent substitution is taking place within the AF. The first area is associated with weapon system design. The solvents are identified through design and logistic reviews which specify maintenance operations and the consumable materials associated with intended processes. If the design and logistic personnel are aware of the hazardous materials, the solvents can be replaced before technical orders are printed and maintenance processes approved. The processes approved at this level drive the resulting maintenance actions which require the hazardous solvents at field and depot level. For clarification, this level is defined as the acquisition level.

The second area concerns the logistic centers (depots) which repair and refurbish weapon system components. The centers are responsible for large quantities of hazardous solvent use in processes. Unfortunately, the centers repair multiple weapon system components on the same process lines making it difficult to replace solvents without impacting other systems. Process engineers at the centers make material substitutions of the solvents used in the center processes. These changes sometimes require modifications to technical orders and instructions. This level is defined as the depot level.

The third area concerns field level maintenance (both flightline and shop). Maintenance processes used by the crews are documented in technical orders and instructions which are ultimately controlled by the system program managers. The

maintenance crews are not authorized to change processes (including making solvent substitutions) without direct approval from the program office for that system. In some cases, the Deputy Chief of Maintenance at the field base can allow substitutions on a limited time basis, but given risks associated with material incompatibilities, this is not common practice. This level is defined as the field level.

System Program Managers (SPM) maintain ultimate authority over the maintenance processes. Technical support personnel within the SPM evaluate substitutions suggested from field and depot organizations. Due to manpower and funding restrictions, it is sometimes difficult for the SPM technical staff to qualify replacement solvents without direct contractor involvement. As a result, field suggestions are difficult to approve in a timely manner without funding for qualification testing (usually conducted by the weapon system contractor). In addition, warranty issues involved with aircraft engines may require contractor qualification of the process prior to government approval.

Substitution decisions at all levels involve the evaluation of attributes and identification of pertinent criteria. This requires comparison of attributes across alternatives and the development ratio scales. For example, parameters like environmental impact are difficult to quantify and are usually addressed by comparing whether solvent A has a higher or lower value then solvent B (for example, solvent A has an environmental impact twice that of solvent B). Although this involves characteristics like toxicity, an actual cardinal scale value is difficult to obtain (for example, solvent A has an environmental impact value of 10.5, and solvent B has a value of 3).

The Subsystems SPO at Aeronautical Systems Center (ASC/SMEN) in connection with SA-ALC and OC-ALC established the Propulsion Environmental Working Group (PEWG) to address propulsion industry environmental issues. The PEWG includes industry engine contractors as members and is chaired by representatives

from the engine Product Group Manager at SA-ALC. The group includes field and depot level personnel as well as SPM representatives which are able to approve technical changes and solvent substitutions. The group primarily functions as a working level action team. The PEWG identified the need for test requirements to prescreen potential substitute solvents prior to qualification testing and released potential substitutes currently used by PEWG members in wipe cleaning operations (9:2).

Substitution Process: Acquisition Level

The acquisition group at ASC/SM evaluates solvent substitutions on a case-by-case basis. The organization resolves decisions involving engines for which ASC/SM has management authority (direct or delegated). Replacements are evaluated by the engineering office (SME) in connection with logistics, safety and environmental support personnel. Emphasis is placed on material compatibility and system safety as well as logistic factors (for example, product availability). The organization also relies heavily on contractor approval and qualification of the substitute prior to authorizing its use by field personnel. The decisions usually involve current field level applications and single proposed substitutes. The proposed substitute is usually identified by either field or depot personnel, engine contractors or solvent manufacturers. SME does not use an MCDM model to evaluate alternatives but relies on engineering judgment and input from logistic and technical personnel at the depots and contractor facilities. Comparisons of solvent alternative attributes is not formalized which makes it difficult to substantiate decisions.

Substitution Process: Depot Level

The logistic centers are tasked to maintain and refurbish weapon systems. In the aircraft engine world, this typically refers to SA-ALC (repairs PW engines) and OC-ALC (repairs GE engines). Recent changes in the management structure of weapon systems have created Product Group Managers (PGM) which have responsibility for specific systems. The PGM for engines is at SA-ALC/LR.

For each engine type, there are two important groups which must be addressed. The first is the depot team which is responsible for repair and refurbishment processes at the depot. Substitution decisions are made by the technical support team which rely on input from process engineers. Decisions involve material comparability, process comparability, cost and environmental/health impacts. Since they are directly involved with the process on a day-to-day basis, the engineers are able to rely less on contractor input and more on their own engineering data and judgment. Activities may include refurbishing engine components, cleaning turbine blades, and vapor degreasing parts.

The second group is the team which manages the field maintenance (and much of the depot level maintenance). This team decides substitution issues which are forwarded from operational air bases. Decisions are made on a case-by-case basis similar to the process used by ASC/SM. Given the operational impact of their decisions, this team relies more on contractor approval of substitutes prior to authorizing changes. It also has change authority on the technical documentation which introduces additional funding requirements. For example. SA-ALC/LPE which maintains the TF39 and TF56 engines does not have the original data used to qualify the cleaners currently used. As a result, they are unable to qualify new replacements without support from the engine contractors. Given financial and manpower constraints, it is difficult for the office to qualify substitutes (10). Similarly, OC-ALC/LPARR which manages the TF33 and J79 engines addresses

maintenance substitution processes. They use in-house data and evaluate process requirements which are then provided to the solvent venders. The venders must prove that the replacement solvent meets process requirements (burden of proof is on the vender). The evaluation only approves that a cleaner is applicable, the office does not pick the best alternative but identifies approved substitutes (11). Similar to SME, the process engineers that decide the issues typically do not use MCDM techniques. Both SA-ALC and OC-ALC rely on technical support from SA-ALC/TIES which manages the military specification and qualified parts list for biodegradable, water dilutable, environmentally safe cleaning compounds (12:1). The specification lists requirements for cleaning compounds including cleaning efficiency, environmental impact, human safety and material compatibility. The specification does not address specific qualification tests required for specific applications.

SA-ALC/TIES is currently preparing a list of criteria that should be addressed in the substitution process (13: 3-7). The first criteria is the environmental impact which combines environmental and safety factors. The criteria is quantified using LD_{50} and LD_{100} data using fathead minnow and shellfish tests and personnel exposure limits established by OSHA and NIOSH. It also relies on EPA biodegradability test requirements, classification status as an ozone depleting substance and/or hazardous air pollutant. Performance is the second criteria which involves evaluation of the effectiveness of the cleaner and its applicability to the process. The last criteria is corrosion which involves material compatibility requirements of the cleaner.

The strategy behind MIL-C-87937B is to provide a qualified parts list (QPL) of acceptable solvents to use as aqueous cleaners. The document is a performance specification which may be referenced in TOs thereby reducing the need to list chemical brand name cleaners. The approach places qualification and competition constraints on the solvent manufacturers. For example, instead of listing Cleaner A as the solvent for a

cleaning process in the TO, the document states to clean using a MIL-C-87937B material. Each vender must prove their product meets the specification requirements. Once they have, the stock number for the product is placed on the QPL. The maintenance personnel only have to order one of the approved stock numbers to get an appropriate cleaner. There isn't a need to evaluate each cleaner because the specification has already filtered them. Any of the cleaners on the QPL should work. Usually, the lowest priced stock numbered item on the QPL is purchased by supply personnel who then use it to fill orders from maintenance personnel.

An advantage to this approach is the elimination of brand name references in the TOs which has led to legal problems concerning fairness and open competition. The method also places test costs on the venders and reduces purchase prices through market forces. It also allows for addition/deletion of chemicals from the QPL without modifying technical orders. There are however several concerns associated with the approach. One is the potential that personnel ordering QPL cleaners are not guaranteed specific brand names unless they specify stock numbers assigned to that chemical (sometimes different cleaners are assigned the same stock number in reference to a QPL which makes management of supplies easier). The approach also provides a list of cleaners without preferential ranking. This can be an important consideration when a base is concerned with a particular attribute, like toxicity or cleaning efficiency. Further evaluation of the cleaners may be required to address process specific constraints including compatibility with unique materials and performance requirements.

There currently is no specification or QPL for solvents used in wipe cleaning applications. Although such a specification would provide a listing of qualified cleaners for general applications, aircraft engine maintenance processes would most likely require additional evaluation prior to authorization (9:2). Given a listing of approved cleaners

from a QPL, there still exists a requirement to chose the optimal choice contingent upon base/field considerations including cost and environmental impact.

Substitution Process: Field Level

Field level personnel are confronted with substitution problems on a recurring basis. As more and more constraints are levied on air bases, maintenance shops are being required to reduce or eliminate hazardous solvents. Since maintenance personnel are required to operate within the technical documents for which they do not have change authority, the bases are caught in the middle of the substitution problem. Base personnel routinely submit potential substitutes back to the SPM or management authority for approval. Typically, the bases do not conduct research efforts to evaluate multiple alternatives but request approval to use substances they become aware of, either through other maintenance processes or solvent venders. The senior maintenance personnel have limited authority to authorize the use of replacements, but the practice is not common.

A recent study by Rockwell for the EPA (California) evaluated the replacement of chlorofluorocarbon wipe solvents. The study identified effective cleaners which where non-chlorofluorocarbon and had low volatile organic contents. Applications of the cleaners included metal finishing, bonding, coating, upholstery, inspection, laboratory, and printing. The study evaluated a total of twenty seven cleaners, conducting six physical characterization tests and three performance tests. The tests included health and operational use considerations. The research showed that due to environmental requirements, vapor pressures, quantity of volatile organic compounds and performance standards must be considered in the solvent evaluation. The study provides ranking of solvents based upon attribute values obtained from testing and operational facility tests (14: 2-5).

Contractor Processes

Although engine contractors do not use formalized MCDM techniques in solvent substitution processes, they have established criteria that must be considered prior to solvent qualification and evaluation. Pratt and Whitney established comparability requirements for cleaners including hot corrosion tests on metal alloys and testing impacts on non-metallic materials (reference PW Hot Corrosion, and Non-Metallic). The requirements are used to qualify general wipe solvents used on their engine components. Pratt & Whitney also requires stress corrosion testing (ASTM F945-85) and stock loss test requirements for wipe solvents (SAE ARP 1755A) (15:1). General Electric uses an internally developed test document to prescreen solvents prior to their qualification (16:2). The document combines environmental requirements with health and safety constraints. Allied Signal Aerospace Company uses an internal document to specify requirements for material compatibility's of new cleaners (17:3-5). The specification addresses corrosive effects of materials and the cleanliness requirements for various applications. The document classifies five types of cleaners and establishes specific qualification tests to address test methods and cleaning types.

In connection with the PEWG, I presented test requirements for evaluating wipe cleaning solvents. The research combined material compatibility and environmental requirements used by the PEWG members (including those identified above) in their initial qualification procedures of wipe solvents. The research identifies the importance of material comparability and environmental requirements in the substitution process (18:2-5).

Multiattribute Utility Theory

Many multicriteria decision making processes have been developed and applied to the problem of choosing a particular alternative given multiple attributes and objectives. Since the solvent substitution problem involves at least the consideration of multiple attributes and objectives and the ranking of alternatives, multiattribute utility theory should be considered. MAUT is a way of capturing decision makers preferences and building models to solve decision problems involving multiple attributes.

MAUT is used to solve complex decision problems involving multiple objectives and criteria. The theory is based on the concept that the decision maker (DM) will try and maximize an underlying value function U (19:39-40). Unfortunately, it is difficult to combine criteria and establish the value function. According to Zeleny, "MAUT reduces the problem of assessing the multiattribute utility function into one of assessing a series of *unidimensional* utility functions. Such individual estimated "component" functions are then glued together again; the "glue" is known as "value-trade-offs" (20:409).

According to Keeney and Raiffa, the approach can be summarized as follows: let "a" represent a feasible alternative from a list of alternatives denoted "A". Each alternative "a" has attributes denoted "X" (there are n number of them). The problem is to choose "a" from the list of "A" which provides the best set of corresponding $X_1(a).....X_n(n)$ and therefore the best solution. To do this, need to combine $X_1(a).....X_n(a)$ into a value function $U(X_1,X_2,...X_n)$. The trick is to find a function "f" where

$$V(X_1, X_2,...X_n) = f\{V_1(X_1), V_2(X_2), ...V_n(X_n)\}$$

with V_i designating a value function over the attribute X_i (21: 68). There are many forms which the function f may have. The problem therefore is finding the univariate

value functions V_is and combining them together to obtain the multivariate value function $V(X_1, X_2,.....X_n)$.

The theory is best illustrated with an example. Consider a problem described by Chan in which a commander must choose the best tracking system for a space-based defense system. There are three potential systems which have been evaluated in terms of three attributes; cost, time to completeness and effectiveness. For the attributes cost and time, less is preferred. For the effectiveness, more is preferred. Each system alternative attribute was determined without comparing the different alternatives (cardinal values not ratio scales). First, the attributes must be expressed in terms of utiles which requires development of the univariate value functions for cost, time and effectiveness. The problem is combining the attributes into a multivariate value function given the decision makers preferences. Data from the decision maker is obtained and independence issues addressed. After determining the scaling constants and weights from the DM's value-trade offs, the value function is determined using the multiplicative form

$$U(C,T,E) = 0.2\,U_C(C) + 0.4\,U_T(T) + 0.2\,U_E(E) + 0.0745\,U_C(C)\,U_T(T) + 0.0372\,U_C(C)U_E(E) + 0.0745\,U_T(T)U_E(E) + 0.0139\,U_C(C)U_T(T)U_E(E).$$

where U_C , U_T and U_E are the univariate value functions for cost, time and effectiveness, respectively (22). Each alternative A, B and C is then evaluated by putting the alternative's cost, time and effectiveness attribute values into the function.

There were nine specific data sets required from the DM including attribute trade-offs and comparisons required to establish independence of parameters and determine the parameters. The problem was simplified by providing the univariate value functions. In actual applications, the DM value system must be captured and the univariate value functions developed using lottery techniques. For problems with a large number of

attributes, the data requirements can become difficult to obtain and manage. In addition, the decision maker must be familiar with the concepts involved with the theory to correctly capture his preferences. Zeleny included this requirement in his five step MAUT process. The steps are;

1. Introduce the DM to the concepts involved
2. verify relevant independence conditions to determine the utility decomposition form
3. assess component utility functions, usually through interrogation of the DM
4. determine parameters, weights and scaling factors for the multivariate function
5. test consistency of compound utility function against DM's actual rankings and preferences (20:40).

Janssen, et al stated that problem definition, including objective identification and clarification of criteria is the first step in developing a multicriteria environmental analysis (23: 1-2). Ellingson and Gallogly used this concept in their research to develop a multicriteria decision model for prioritizing AF restoration programs (24:47-48). After determining the problem objectives, criteria and pertinent alternative attributes, they developed a multivariate value function using survey results from a single decision maker. Their research showed the importance of the scaling values used in the multiattribute value function.

Independence Requirements

One of the important concepts associated with the analysis of decision alternatives is the issue of attribute independence. There are three main types of independence. An attribute is preferentially independent of another attribute if preferences for a specific

outcome associated with that attribute do not depend on the level of the other attribute. Consider an example from Clemen's text on decision involving two attributes; time to completion of a project (X) and project cost (Y). If a project time of 5 days is preferred over a project time of 10 days regardless of the project cost, then Y is preferentially independent of X. Similarly, if a cost of $10,000 is preferred over a cost of $20,000 regardless of completion time, X is preferentially independent of Y and the two attributes are considered mutually preferentially independent (25:477).

Utility independence is more stringent the preferential independence. According to Clemen, "An attribute Y is considered utility independent of attribute X if preferences for uncertain choices involving different levels of Y are independent of the value of X" (25:478). Consider the earlier example involving attributes X and Y. Given a 50% chance of time to completion of 5 days and a 50% chance of a time of 10 days, if the certainty equivalent remains the same regardless of the cost value X, then Y is utility independent of X. If also X is utility independent of Y, the two attributes are mutually utility independent (25:478).

Additive Independence is an even more stringent independence requirement. Additive independence holds if "changes in lotteries of one attribute do not affect preferences for lotteries in the other attribute..." (25:482). If additive independence holds, you can compare alternatives one attribute at a time. Consider the X and Y attributes mentioned before. If X and Y are mutually utility independent and the DM is indifferent between lotteries A and B where

lottery A: provides outcome (x_0, y_0) with probability 50%
provides outcome (x_1, y_1) with probability 50%
lottery B: provides outcome (x_0, y_1) with probability 50%
provides outcome (x_1, y_0) with probability 50%

then the attributes are additive independent. In order to model DM preferences, additive independence across attributes is required to use the additive utility functional form (25:482) which is a simplified form of the multiplicative form discussed in the next section.

Multiplicative Utility Function

Given that mutual preferential independence and mutual utility independence holds across the attributes, the multiplicative utility function can be used. For n different attributes and with $U_i(x_i)$ and k_i corresponding to the individual utility function and scaling constant, the form is

$$U(x_1, x_2, \dots x_n) = \prod_{i=1}^{n} (k\, k_i\, U_i(x_i) + 1)$$

where x_n represents the n^{th} attribute and k is the non zero solution to the equation

$$1 + k = \prod_{i=1}^{n} (k\, k_i\, U_i(x_i) + 1).$$

The value for k_i is the utility for an outcome having the best value level on X_i and the worst levels on all other attributes X_n. This can be solved directly using the lottery technique shown in Figure 1 where $p_i = k_i$ (25: 490). The comparison determines a value for the probability P which makes the DM indifferent between a sure outcome (highest value for attribute 1 (Xi^*), but lowest for all other attributes (Xj0)) and a lottery of outcomes (best of all attribute values and worst of all attribute values).

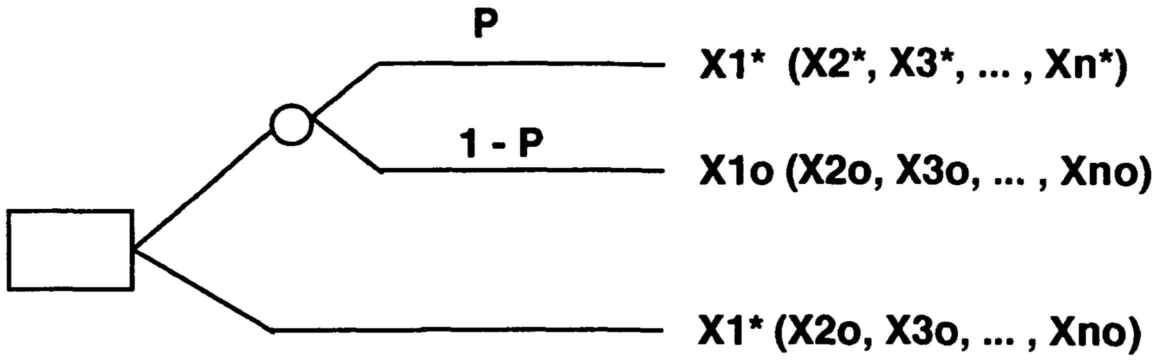


Figure 1: Lottery Technique for Evaluating Multiplicative Utility Scaling Parameter.

Wakker provides methods for determining additive value functions for decisions without using ojective probabilities and lottery tools (26:1,2). Additionally, his research details methods for developing additive utility functions (referred to as representing functions) which model DM preference relations. In particular, he proposes the Central Theorem for Additive Representations which says that given topological assumptions on factor subsets, if the preference relation is coordinate independent, continuous and transitive, there exists jointly cardinal continuous additive value functions $(V_i)^n{}_{i=1}$ for the relation if the preferance satisfies the hexagon condition. The hexagon condition is a requirement involving plotted equivalence classes in reference to criteria axes and the transitivity of preferences within defined equivalence classes (26:49). The process is a departure from traditional utility theory methods as detailed by Zeleny and others.

Different software programs have been developed to solve MAUT problems using multivariate utility functions. For example, researchers at Arizona State University developed a software program titled Power Utility which solves management problems using MAUT techniques. The program requires the user to be familiar with MAUT concepts and requires identification of the scaling constants and weights prior to analysis (27).

The problems associated with the capturing of DM preferences, large data requirements and value trade-offs and decomposition form complexities have hindered the use of MAUT as an effective application tool. The analytical hierarchical process (AHP) provides a potential solution to the intensive data demands associated with the use of MAUT. The method assumes the independence requirements discussed above and uses an additive value functional form.

Analytical Hierarchical Process

The Analytical Hierarchical Process (AHP) is a management tool which uses pairwise comparisons of components to solve decision problems. The process uses hierarchic structures to represent a problem and then develops alternative priorities using DM judgments (28: 11-21). It uses several assumptions to simplify the procedure which makes it attractive as an application technique. Many articles have been published which detail the use of AHP in alternative ranking problems including the use of the technique to prioritize environmental, safety and health technology needs (29: 6) and the selection of the best working fluid in heat engine cycles (30: 424).

There are several problems associated with the use of AHP. One of the problems is the issue of rank reversal. Rank reversal refers to the concept of the alternative rankings changing when new information is introduced into the problem. For example, consider a problem where three alternatives were ranked with alternative A preferred to B, B preferred to C. If a new alternative D is introduced, it is possible that the resulting ranking will show D preferred to A, but C preferred to B et cetera. That is, the ranking of the alternatives may not be preserved when new information is introduced into the problem. According to Saaty, there is no reversal of rank when absolute measurement has been used

and new alternatives are added (or deleted). Problems arise when relative measurement is used and new alternatives are added. Rank reversal can occur when one alternative dominates a criteria, and another alternative dominates another criteria. Adding a new alternative can cause rescaling and thus rank reversal if using relative measurement ratio scales . His research showed that rank reversal is caused by structural dependence of criteria on alternatives (31: 28). In other research, Saaty and Vargas showed that using three methods of scaling, distributive, ideal and utility modes, yield the same ranking of alternatives with high frequency except for the case of copies or near copies of alternatives. In this case, the distributive mode always reversed rank of the alternatives. The authors point out that this is legitimate since the mode specifies the uniqueness of the most preferred alternative is important (32: 4). Other authors have addressed the rank reversal issue, including Dyer who suggested that the problem can be corrected by incorporating concepts of MAUT into the process (33: 249).

The process recommends the evaluation of alternative attributes on a 9 point scale and requires the comparison of alternatives and criteria to determine the multivariate value function. There is also a question of the measurement of consistency of the DM's answers. Saaty recommended a flat 10% inconsistency method based on DM's importance ratios used in the process (28: 21) while others have proposed statistical approaches (34: 19) and the use of stricter consistency requirements for three and four attribute criteria matrices (35: 575).

The process is best illustrated with an example. Consider a problem described by Chan in which three vehicles are evaluated with respect to their risk, performance and schedule (picking the best trans-atmosphere vehicle). At the first hierarchy, the criteria are compared and determined using eigenvector approach. Each criteria is compared to the other two criteria to construct a matrix of relative values. Using the constraint that the criteria weights sum up to one (assuming additive function), the matrix is solved for the

risk, performance and schedule weights. At the next level, each alternative is compared to the other two alternatives with respect to one of the criteria (for example, risk). The relative values are used to construct a matrix which is used to determine the criteria value function values for the three alternatives (for example $V_{risk}(A)$, $V_{risk}(B)$, $V_{risk}(C)$). This is continued until all of the alternatives have been evaluated with respect to all of the criteria. The resulting value functions are combined with the weights to provide the ranking of the alternatives. In this example, the values provide

$$V(A) = 0.249\ V_{risk}(A) + 0.593\ V_{perf.}(A) + 0.158\ V_{sched.}(A) = 0.537$$
$$V(B) = 0.249\ V_{risk}(B) + 0.593\ V_{perf.}(B) + 0.158\ V_{sched.}(B) = 0.161$$
$$V(C) = 0.249\ V_{risk}(C) + 0.593\ V_{perf.}(C) + 0.158\ V_{sched.}(C) = 0.302$$

Since vehicle A has the highest value function value, it is the best choice followed by C. The data requirements for this process were much less stringent then those associated with the MAUT process (22).

The AHP has been successfully modeled by several software packages. The software package ExpertChoice has been successfully used to solve decision problems. The package uses AHP and an interactive menu to allow limited sensitivity analysis of DM answers. It also calculates an inconsistency ratio and provides suggested inputs for reducing inconsistencies (36). Although user friendly, the system has limited graphics capabilities. Decision Sciences Plus is another software package which solves AHP problems. The package is menu driven and user friendly, providing status updates on problem definition. The package also has a more complete sensitivity analysis capability and graphics capability then Expertchoice (37).

AHP and MAUT Comparisons

Given their applications, it is not surprising that researchers have compared the two methodologies. Bard used both AHP and MAUT to select an Army cargo handler and investigated strengths and weaknesses. The decision involved three alternatives, 12 attributes and five decision makers. The author identified problems associated with both techniques including the 9 point scale used in AHP and difficulties in assessing scaling constants in MAUT. Although the DMs had difficulty answering MAUT survey questions, the overall results for both methods closely agreed. This results from the fact that both techniques have built in redundancies and are insensitive to minor discrepancies in reasoning (38: 17, 18). The research suggests that AHP should be used for problems involving a large number of attributes whose outcomes can only be measured on a relative scale.

Foreman addressed the similarities of the two methods in his analysis of AHP. According to his work, the only significant difference between the two methods is in the derivation of the alternative value function (when MAUT is implemented using AHP hierarchical structure and ratio scale priorities for all levels but the alternatives). Although AHP uses pairwise comparisons while MAUT uses lotteries, the two methods are more alike than they are different (39: 24).

Another team of researchers used AHP and MAUT to rank order seven cities in terms of their livability (40: 1). They suggested combining the strengths of the two methods into a management tool. One potential integration included the use of the weighing technique used in AHP and the scoring of alternatives using MAUT interval scale procedures.

Chan addressed the similarities associated with the two methodologies as well. Given that the overall utility and value functions associated with both methods are

strategically equivalent, the resulting rankings from the approaches should agree. Furthermore, if mutual utility, preferential independence and additive independence can be established in MAUT, the overall multivariate utility function can be expressed as an additive function similar to the function used to rank alternatives in AHP (22).

The concept of inconsistencies becomes an issue when comparing models. The AHP addresses inconsistencies by determining the inconsistencies of DM value answers at each hierarchy level. The MAUT model inherently assumes the DM's inputs are not inconsistent and uses the responses to determine scaling coefficients directly. The method is not structured to address inconsistent responses (41: 381-385).

Another comparison technique involves the use of strategic equivalence. According to de Nuefville, strategic equivalence means that the value functions lead to the same ordering of preferences over the attribute ranges (42: 364). This is an important concept because if applicable, allows the use of less complex utility/value functions to rank order alternatives, thereby avoiding determination of added scaling factors required by complicated functions.

Group Decision Making

Many MCDM problems involve group decisions where there is more then one decision maker. There are advantages and disadvantages associated with group decision making. Unfortunately, the added number of decision makers increase the complexity of capturing preferences and determining criteria weights. Various researchers have identified techniques for resolving group decision issues.

Keeney and Kirkwood defined a representative form for the group utility function (GUF) as:

$$U(x_j) = \sum_{n=1}^{s} \lambda_n u_n(x_j) + \lambda \sum_{n,t=1}^{s} \lambda_n \lambda_t u_n(x_j) u_t(x_j) + \ldots + \lambda^{s-1} \lambda_1 \lambda_2 \ldots \lambda_s u_1(x_j) \ldots u_s(x_j)$$

The parameters n and t refer to the number of criteria and decision makers respectively. The group utility function U and the univariate utility functions u_n's are between zero and one. The parameters λ and λ_n are scaling constants between zero and one for all n. When $\lambda = 0$ the equation takes on the additive form:

$$U(x_j) = \sum_{n=1}^{s} U_n(x_j)$$

The scaling constants λ_n, n=1,...,s, represent value trade-offs of the decision makers. (43:434). According to the authors, the GUF can be specified by a "dictator" who picks *scaling constants* impartially to incorporate the preferences of all group members in to the decision, or by using the collective response of the group to determine the scaling constants. In the first case, the process is similar to the technique used to determine parameters for a single decision maker. The second case involves a combination of the individual's utility functions and evaluation of the individual group utility function (IGUF) for each member of the group. The GUF is then constructed as a weighted aggregation of the IGUFs. This process includes interpersonal comparisons of preferences and requires the measurement of the strength of individual preferences. Given complexities associated with the above method, it can be difficult to determine the overall GUF. The group decision making conflicts may be resolved without generation of the GUF if value conflicts within the group are resolved.

Seo and Sakawa identify three ways to provide a measure for determining value conflicts among decision makers. The first one is the probabilistic approach which

> "...treats the objects to be evaluated as uncertain quantities and assesses their probability distributions to represent the diversification of evaluation among multiple decision makers. As a modification to the probabilistic approach, an entropy model can be used for assessing the probabilities." (reference 44: 240).

The second technique is the fuzzy approach which is nonprobabilistic and "treats the linguistic ambiguity of some assertions with semantic unpreciseness. It is based on a posterior assessment via subjective decision." (44: 240). The third is the stochastic approach which concerns the partial identification of the GUF. It is different from the other two approaches in that it "requires to assess the risk attitudes of the presumed group utility functions." (44: 240).

Other researchers have used different techniques for assessing the GUF. Erkut and Moran used a group process rather then the aggregation of individual inputs to determine their parameters (they used AHP to solve their problem). The group process involves the decision makers working together as a *group* to determine one set of inputs for the model. The process facilitated the individual members understanding of the significance and meaning of each criteria and clarified misunderstandings and differences in the interpretation of data. The group process also utilizes the dynamics of power and influence within the group without explicit modeling (45: 94). Prince also used this group interaction to score alternative criteria without generating criteria univariate value functions (46).

When the aggregation of individual inputs is used, the results must be combined to provide a single set of inputs. One method for doing this is to use a geometric mean of individual comparisons. According to Aczel and Saaty, the geometric mean is the appropriate technique for combining judgments in the AHP model because it preserves the reciprocal property of the combined pairwise comparison matrix (47: 63). Bard used this technique to evaluate multiple inputs from his decision makers (38: 1). This method treats

all members of the group as if they were equal in terms of influence and power. It is questionable whether influential decision makers within the group would accept the final ranking results. Erkul and Moran discussed the establishment of relative influences among group members as means to model the dynamics of power and influence within the group (process described by Seo, et al). The authors indicate problems associated with the group accepting the resulting alternative ranking determined through this approach (45: 94).

Review Summary

Although government and contractor agencies have released qualification and screening requirements for evaluating replacement cleaning processes, they do not use a structured decision model to evaluate potential replacements or have defined criteria and attributes identified. Recommended factors are process compatibility, cost, environmental and health impacts and cleaning performance/effectiveness. Constraints include material compatibility, legal compliance and financial requirements.

Both MAUT and AHP have been successfully applied to the area of picking alternatives from a list of potential candidates. There are advantages and disadvantages to both methods and different independence requirements. The optimal management model may be a combination of the techniques which might provide an accurate modeling of DM preferences and ranking of alternatives without rigorous pairwise comparisons.

Researchers have used a variety of techniques to combine inputs from multiple decision makers for the determination of utility function weights and value trade-offs. Their research has identified strengths and weaknesses associated with the various methods indicating the need to match and tailor the overall decision method and model to the specific decision problem.

Chapter 3

Research Methodology

The purpose of this chapter is to outline the methodology used to achieve the research goals. Several steps are involved including characterization of the wipe solvent process, development of solvent criteria values, development of the AHP and MAUT decision models, implementation using survey techniques, and the analysis of utility/value models and rankings. Results of the research will be provided and discussed in the next chapter.

Problem Characterization

This step involves identifying the test case parameters, researching solvent characteristics and narrowing the alternative list. An actual maintenance problem was identified by one of the solvent experts concerning the replacement of Methyl Ethyl Ketone (MEK) used to surface clean engine turbine blades. Trained maintenance personnel at depot level use MEK to remove dry film lubricant and grease/grime from engine blades prior to inspection of the dove tail ends of the blades. The lubricant is used to protect the blade ends during installation and engine operation. After the blades are inspected, the lubricant must be reapplied and baked on to properly cure it. The blades are constructed from Ti-64 (titanium alloy). The process is detailed in technical references which must be modified to incorporate changes. The substitute cleaner must meet test requirements of ARP 1755A and ASTM F945-85.

Since the process will be conducted at depot level, the replacing solvent must meet vapor pressure and flash point constraints at the location. The flash point must be above 140 degrees Fahrenheit, with a vapor pressure of less than 45 mm Hg. Regulatory

requirements mandate the material not be listed as a carcinogen, hazardous air pollutant or ozone depleting substance. The material should be biodegradable under 40 Code of Federal Regulations (CFR) test requirements, however this is not a constraint.

The depot engineering support team has management authority over the replacement change and technical documentation.

Once the parameters are identified, solvent alternatives must be researched and specific characteristics identified. Due to financial and schedule limitations, existing test data will be used to develop the criteria scoring attributes. Specifically, research conducted by Eichinger in connection with material safety data sheets, and vender supplied information will be used to generate the solvent data. Cleaning tests will be included in the documentation. In practice, the cleaning effectiveness tests should be conducted using actual parts, soils and technicians. Since this is not possible for this effort, existing coupon test data involving similar soils will be used to simulate effectiveness testing. Technical personnel involved with the actual field cleaning will verify the applicability of the coupon tests.

Solvent Criteria

Researchers, including Poone et al and Tiley, have identified solvent criteria that are applicable to this problem. The criteria are environmental impact, cost, process compatibility, health/safety impact and cleaning effectiveness. Although researchers have provided guidance in assessing criteria (13: 2), the exact functional forms of the criteria are unknown. For example, environmental impact criteria involves factors including toxicity, biodegradability, volatility and regulatory requirements. The impact of these factors must be determined along with the overall criteria values for each alternative.

Although identified as an important consideration in the replacement problem, it is difficult to quantify values for criteria when their functional form is unknown.

To overcome this, a team of experts will be used to scale the solvent criteria values and develop the criteria functions. This process is similar to the technique used by Prince and Bard in their research of scoring criteria. The team includes technical personnel from AF aircraft engine agencies and commercial aircraft engine companies that are currently involved in the solvent replacement effort. The team is listed in Table 1. The criteria values will be determined by a team of cleaning experts to capitalize on the existing knowledge bank.

Reference No.	Position	Organization
1	Material Engineer	Technical Support, Kelly AFB
2	Material Engineer	Engineering Support, Kelly AFB
3	Material Engineer	Engineering Support, Tindall AFB
4	Material Engineer	Materials Laboratory, WPAFB
5	Env. Engineer	Concurrent Technology Corporation
6	Env. Engineer	Allison Engine Company
7	Env. Engineer	Pratt & Whitney Aircraft Engines

Table 1: Solvent Expert Team

In particular, each team member will independently evaluate the solvent data. Based upon the data, they will scale the solvent attributes for each criteria based upon a seven point scale as recommended by Saaty and others. Resulting scores from the experts will determine the final values using the geometrical mean as suggested by Saaty and Aczel (47:63). For example, consider Table 2 where criteria values are determined from solvent attributes for each potential solvent. The Table shows how expert number one scored three solvents (value column) given information on their biodegradability, flash point, vapor pressure and regulated requirements.

Criteria: Environmental Impact Expert: Number 1

Solvent	Value (utiles)	PEL/TLV	Flash point (deg F)	Vapor Pressure (mm Hg)	Odor
Solvent A	5	50	120	2	none
Solvent B	6	100	110	5	strong
Solvent C	4	----	115	3	mild

Table 2: Example Expert Result (3 Alternatives, 4 Factors)

Once the seven experts have scored the solvents, their data will be combined as shown in Table 3. Table 3 shows an example of the combination of data to determine the resultant

	Expert 1 Criteria			Expert 2 Criteria			Expert 3 Criteria		
	I	II	III	I	II	III	I	II	III
Solvent A	3	5	6	7	8	5	3	4	6
Solvent B	5	4	5	7	8	4	2	3	7
Solvent C	4	9	7	3	5	6	3	8	2

Table 3: Example Criteria Resultant Matrix (3 Experts, 3 Alternatives, 3 Criteria)

data matrix and criteria values. The example shows three experts that have scored solvents A, B, and C on three different criteria (I, II, and III). Their values for each solvent and criteria are combined with the result $V(X_1, X_2, ..., X_n) = (X_1 * X_2 * ... * X_n)^{1/n}$. Note that each criteria data set from the experts on the alternatives is normalized to maintain the correct ratio scale.

Criteria Function Forms

The experts will also evaluate attribute factors and provide a list of which factors they consider important in quantifying the criteria. The list of factors provided to them will only be a reference list, generated from the solvent data provided by the manufacturers and research studies. The experts are not limited to the list of factors but are encouraged to include anything they consider relevant.

Factors which the majority or more of the researchers identify will be considered significant. These factors will be used to form the minimum test requirements needed to evaluate potential solvent alternatives. The expert team survey, including attribute factor list and cover letter, is provided as Appendix A.

Analytical Hierarchical Process Model

Using the criteria and solvent attributes determined by the expert team associated with the test case, an AHP model is developed in accordance with Saaty. The single decision maker will provide model inputs required to determine utility function weights. This requires both an education process to familiarize the DM and a data gathering survey to establish parameters. The survey will determine ratio scale values used to resolve model parameters as established by Saaty. As demonstrated by Erkut and Moran, the software package Expert Choice will be used to solve the model parameters and rank the alternatives. In addition, the software will be used to evaluate model sensitivity to function weights and criteria values. The consistency index parameter will be used to evaluate consistency of DM's answers. The hierarchy for the model using the established five criteria and five solvents is provided in Figure 2. Each level of the hierarchy requires

pairwise comparisons of the members to determine the matrices used for the weights. For example, at the second level, the DM is

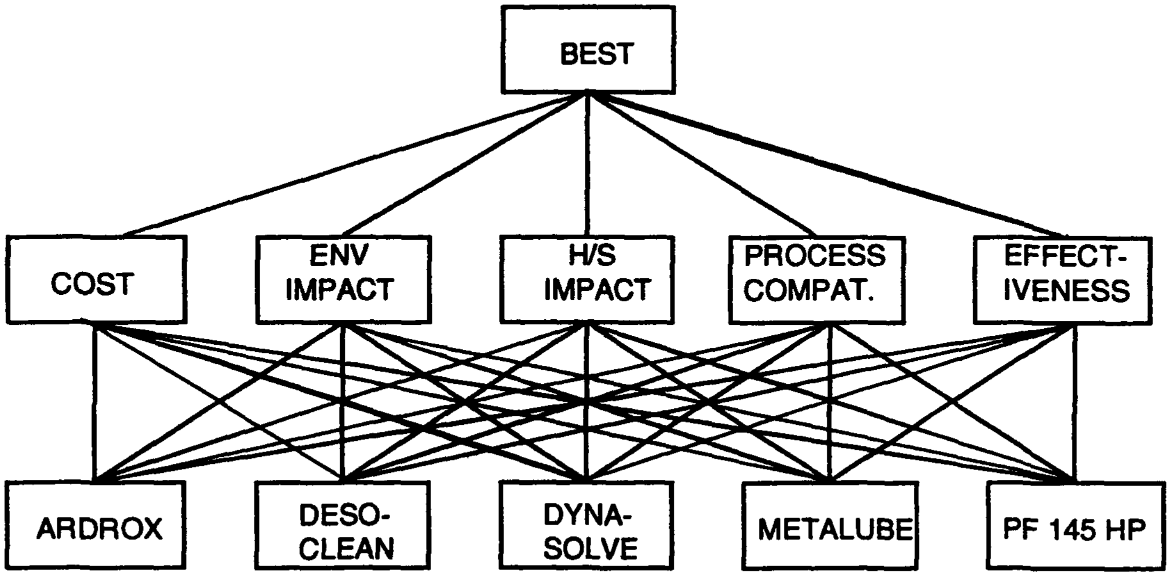


Figure 2: AHP Hierarchy for Model

asked to compare Ardrox]180 BH to Desoclean 45 in reference to their environmental impact on a ratio scale from 1 to 9. A value of 5 means that Ardrox 180 BH is 5 times preferred to Desoclean 45 in reference to their environmental impact values. Each of the alternatives, and the top level criteria, is pairwise compared. The information is used to determine the consistency index values and the weights for the additive value function. The function scores the alternatives in reference to the DM's preferences.

Strengths and weaknesses associated with the model will be discussed with the DM. The resulting ranking of solvents and model performance will be presented to the DM in connection with the MAUT model results. The final value function as determined by AHP will be evaluated later in the model comparison section. Verification of the model will be accomplished through the use of the MAUT normalized values. Validation will be

accomplished through discussions with the DM concerning the final ranking of alternatives and the consistency index values.

Multiattribute Utility Theory Model

Following the methodology of Keeney and Raiffa, an MAUT model will be developed using the test case application. For the given attributes and criteria, a lottery survey will be developed to address model independence requirements and solve for resulting scaling and weight constraints. The survey is provided in Appendix C.

The survey consists of four sections. Section one will specifically test for preferential independence by asking the DM to evaluate solvent criteria given specific levels of other criteria. For example, given two solvents have the same environmental impact, health/safety impact, process compatibility and effectiveness values of 1 out of a 7 point scale (7 is better), which solvent is preferred; solvent A which has a cost of 45 cents, or solvent B which cost $ 21.00. The next question in the set asks the DM to evaluate the same two solvents only with effectiveness values of 7 instead of 1. Each of the five criteria must be tested in reference to the other criteria at separate value levels to ensure mutual preferential independence.

Section two tests for utility independence by asking the DM to evaluate decisions involving lottery results and a certainty equivalent value (CE). Given specific levels for the other criteria, the lottery concerns best and low values for the criteria under evaluation. The following question changes one level for one of the other criteria and asks the DM to determine the new CE. For example, given an environmental impact, health/safety impact, process compatibility and effectiveness values of 1 on a 7 point scale (7 is better), what value for cost would make you indifferent between a sure thing (CE) and a lottery which has a 50% chance of giving a cost of $0.45 and a 50% chance of

giving $ 21.37? The next question asks the same question only with an effectiveness value of 7 instead of 1. Since each criteria must be evaluated in terms of the other criteria, the survey section is rather extensive. Given mutual preferential utility independence, the DM should choose the same CE for the criteria in question regardless of the other criteria levels.

Section three determines the scaling constants used in the multivariate utility function. The DM is asked to evaluate a decision in which he is indifferent between a lottery providing best and worst values for criteria or a sure outcome providing the best value for the criteria being evaluated, yet worst values for other criteria. For example, consider the decision shown in Figure 3. The probability value which makes the DM

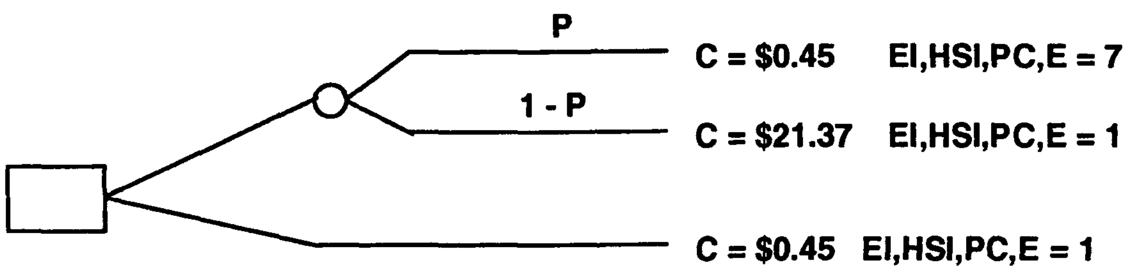


Figure 3: Decision for evaluating the scaling constant for the criteria cost.

indifferent between the lottery and the sure result is the cost criteria scaling constant. The figure uses the abbreviation environmental impact (EI), health/safety impact (HSI), process compatibility (PC), effectiveness (E) and cost (C) criteria.

Section four provides data for determining the univariate utility functions used to map the solvent attributes to utiles. For each criteria, the DM is asked to determine CE values which make him indifferent between high and low value lottery results (each with a 50% chance) and a sure value (CE). For example, what sure cost value (CE) would make

the DM indifferent between CE and a lottery which has a 50% chance of a cost of $0.45, and a 50% chance of a cost of $21.00? Similar questions are then asked using the new CE as one of the potential lottery results. This method provides a mapping of utile values corresponding to criteria values. The data points are curve fitted using a statistical package and plotted. The resulting curve is the univariate utility function which provides the preferences of the DM concerning individual criteria values. Each solvent alternative criteria value is then mapped into utile values using the specific univariate utility functions.

Given utility and preferential independence across the criteria, the scaling constants determined from section three of the survey are input into the multiplicative utility equation for determining the k value (reference Chapter 2). The k value and scaling constants are then combined with the five univariate utility functions determined from survey section four results. The resulting multivariate value function (reference Chapter 2) provides the scoring of the five alternative solvents given their attribute values. The resulting ranking of solvents will be briefed to the DM to determine if his preference was accurately modeled.

The resulting utility function, complete with calculated parameters, will be compared to the additive AHP utility function during the model comparison step.

AHP and MAUT Model Comparison

The solvent rankings for the two models will be compared along with the determined utility/value functions. Specifically, strategic equivalence of an additive utility function, the AHP model and the multiplicative function from the MAUT model will be determined. The weights from the MAUT survey will be normalized and used along with the captured MAUT univariate functions as inputs into the AHP model. This will directly compare the AHP model with an additive utility function and provide verification of the

model. The additive utility function using the same weights and univariate functions will be generated. The resulting rankings will indicate whether the AHP process effectively captured the DM's preferences and verify model methodology.

A two variable case will be used to evaluate strategic equivalence requirements between the additive utility and multiplicative utility functions. According to Seo and Sakawa (44:186-187), when U_A and U_M are strategically equivalent there exists constants $h(y^*)$ and $c(y^*)$ where

$$U_A(x, y^*) = h(y^*) + c(y^*)\, U_M(x, y^0).$$

The superscripts * and 0 refer to the best and worst levels of the attribute. The constant $h(y^*) = U_A(x^0, y^*)$. The above relationship will be evaluated for two variable multiplicative and additive utility functions. Additionally, the functions will be graphed to evaluate function shapes and slopes given specific utility values.

The strengths and weaknesses of the two models will be compared as they apply to the test case. The DM will also evaluate the alternative criteria factors and score the criteria as a test of agreement between the expert team's judgments and the DM's. The results will be input into the AHP and compared with the original AHP preferences. The final results will be presented to the DM to validate the decision models.

Chapter 4

Research Results

Solvent Characteristics

Eichinger's research on potential wipe solvent replacements provided a wide list of alternatives. the leading candidates were narrowed from the original study list. The leading candidates are shown in Table 4.

Potential Solvent Candidates

Brulin 1291	Ardrox 180 BH
Buckeye Shop Master	Desoclean 45
Everclean Blue Gold	Dynasolve 108
Turco 6226	Metalube MC509/4U
Ambersolve 3000	PF 145 HP

Table 4: Potential Solvent Alternatives for Replacing MEK

The solvent manufacturers were contacted concerning chemical characteristics including costs to purchase and toxicity data. Material safety data sheets were also obtained on the chemicals. From the above list, five alternatives which best met replacement requirements were chosen for additional consideration. The five chemicals are Ardrox 180 BH, Metalube MC509/4U, Dynasolve 108, Desoclean 45, and PF 45 HP. Due to decision complexities involved with pairwise comparisons and data availability requirements, the list was limited to the five chemicals. Data on the chemicals was tabled and included in a survey which was provided to the expert team for evaluation. The survey questionnaire and solvent information is provided as Appendix A.

Coupon test data from the Eichinger study was used to provide an indication of cleaning effectiveness over a variety of material soils. The specific tests were chosen by the field engineer currently working the test case replacement at SA-ALC. Although dry film lubricant was not tested, the engineer considered the test soils adequate to simulate field conditions for this effort. Additionally, experts were assured that all alternatives met material compatibility requirements and minimum criteria requirements. Responses from the survey are shown in Tables 5 through 8.

SOLVENT ALTERNATIVES

EXPERT	Ardrox	Desoclean	Dynasolve	Metalube	PF 145 HP
1	3	1	5	7	5
2	3	1	3	3	2
3	6	6	4	1	4
4	6	1	4	6	4
5	7	6	1	7	6
6	5	2	2	6	1
7	7	1	3	7	3

Table 5: Environmental Impact Criteria Responses

SOLVENT ALTERNATIVES

EXPERT	Ardrox	Desoclean	Dynasolve	Metalube	PF 145 HP
1	6	1	5	7	3
2	3	5	4	3	2
3	7	1	5	7	5
4	5	2	5	7	5
5	7	1	6	1	3
6	5	1	1	5	1
7	7	5	1	7	2

Table 6: Health/Safety Impact Criteria Responses

	SOLVENT ALTERNATIVES				
EXPERT	Ardrox	Desoclean	Dynasolve	Metalube	PF 145 HP
1	5	7	5	5	5
2	5	5	5	5	6
3	5	6	6	5	6
4	4	5	4	5	2
5	7	1	7	7	1
6	-	-	-	-	-
7	1	5	5	1	5

Table 7: Process Compatibility Criteria Responses

The expert from CTC did not rank alternatives for this criteria because he felt there was insufficient information to make a clear decision.

	SOLVENT ALTERNATIVES				
EXPERT	Ardrox	Desoclean	Dynasolve	Metalube	PF 145 HP
1	5	7	6	3	2
2	2	6	4	2	5
3	4	6	5	4	2
4	3	7	5	6	2
5	6	7	6	5	4
6	4	6	5	2	1
7	4	7	6	3	7

Table 8: Cleaning Effectiveness Criteria Responses

The expert team did not evaluate the cost criteria since by design the only factor involved was the purchase cost of the material. The DM evaluates the cost directly to incorporate his value preference into the decision model. The final data matrix including

the cost criteria data is shown in Table 9. Values were determined using the geometric average where the average of terms $X_1, X_2, ..., X_n = (X_1 X_2 ... X_n)^{1/n}$.

SOLVENT ALTERNATIVES					
CRITERIA	Ardrox	Desoclean	Dynasolve	Metalube	PF 145 HP
Env. Impact	5.01	1.84	2.83	4.49	3.12
Health Impact	5.51	1.75	3.14	4.49	2.64
Effectiveness	3.80	6.55	5.24	2.84	2.73
Process Com.	3.90	4.17	5.25	4.04	3.49
Cost *	0.45	15.65	21.37	0.70	10.82

* cost term reflects purchase cost in dollars per gallon of solvent given recommended manufacturer's concentration level fo. this application.

Table 9: Quantified Criteria Matrix

Criteria Functional Forms

A list of factors which possibly impact the five criteria was generated from the data identified during the research phase. Unfortunately, the data described by the factors is not available on the alternatives under consideration. As detailed in Chapter 3, experts reviewed the factors and recommended which should be quantified and included in the criteria functional forms. The factors for which the majority of experts identified (denoted significant factors) have been listed in Table 10. The factors provide minimum test data requirements to evaluate alternative wipe solvents. Detailed inputs from the experts are provided in Appendix D.

Env. Impact	Health/Safety	Effectiveness	Process Compatibility
biodegradability	toxicity	non volatile residue	non volatile residue
toxicity	odor	cleaning time req.	odor
VOC content	haz. consituents	cleaning effectiveness	cleaning time req.
haz. constituents	safety equip. req.	scrubbing effort req.	safety equip. req.
17 industrial toxin list	explosiveness		ignitability
ODS characteristics	ignitability		reactivity
			purchase costs
			training req.
			startup equip. req.

Table 10: List of Criteria Significant Factors

The AHP Model

The DM was carefully briefed on the AHP and MAUT models including basic fundamentals and assumptions. Fortunately, the DM was experienced with operation research techniques and decision models. The quantified criteria matrices developed by the experts provided characteristics for the DM's evaluation of alternatives. As discussed in Chapter 2, the AHP assumes an additive value function and mutual utility independence. As survey was developed, as discussed in Chapter 3, to determine value function weights and evaluate DM's judgment consistencies. The questionnaire and responses are provided in Appendix B. The results are shown in Table 11.

Criteria	Weight Value
Environmental Impact	0.142
Health/Safety Impact	0.478
Process Compatibility	0.105
Effectiveness	0.231
Cost	0.044

Table 11: AHP Calculated Criteria Weight Values

The resulting ranking shown in Table 12 shows that Ardrox is the best choice followed by Metalube MC509 4U.

Alternative	Ranking
Ardrox	0.267
Metalube MC509 4U	0.228
Dynasolve	0.203
PF 45 HP	0.157
Desoclean	0.146

Table 12: Ranking of Alternatives for AHP Model

The overall value function with the determined weights is

$$U = (0.044)U_c + (0.231)U_e + (0.105)U_{pc} + (0.142)U_{ei} + (0.478)\,U_{hsi}$$

where U is the multivariate value function, U_c is the univariate value function for cost, U_{ei} is the univariate value function for environmental impact, U_{pc} is the univariate value function for process compatibility, U_{hsi} is the univariate value function for health/safety impact ,and U_e is the univariate value function for effectiveness.

The overall consistency index for the judgments is 0.040 which is well below the 10% value recommended by Saaty. The detailed computer output from ExpertChoice is provided in Appendix E.

The MAUT Model

An MAUT model was solved using the quantified criteria and DM survey results. The survey was generated specifically to address independence requirements and determine utility function weights and scaling constants. The survey and responses are provided in Appendix C.

MAUT Survey Results

The survey Section 1 was designed to check preferential independence of the attributes. The DM answered the questions concerning specific criteria preferences the same regardless of the other criteria levels. Given the consistency of the results, the attributes are mutually preferentially independent.

The survey Section 2 was designed to check utility independence among the criteria. Given the CE values chosen by the DM for each criteria did not change over the range of other attribute/criteria values, the criteria are mutually utility independent. Since both mutual preferential and mutual utility independence requirements are satisfied, the multiplicative utility function may be used to model the problem as discussed in Chapter 2.

Survey Section 3 was designed to determine the criteria weights/scaling factors used in the multiplicative utility function. The probabilities chosen by the DM equate directly to the scaling values. The DM had great difficulty interpreting the lottery questions and revised his answers (reference the section titled Verification and Validation). Based on the question results, the scaling factors k_i for criteria i are: k_{cost} =

0.15, $k_{env. impact} = 0.60$, $k_{proc. com.} = 0.40$, $k_{health/safety} = 0.80$, $k_{effectiveness} = 0.70$. Substituting these values into the multiplicative value function with $U_i = 1.0$ and $U = 1.0$ as described in Chapter Three provides a scaling value of $k = -0.986$.

Section 4 was designed specifically to capture the DM's preference on the criteria values. This provides the univariate utility functions required to solve the mutliplicative utility function as discussed in Chapter 2. The DM's answers where used as data points defining the univariate utility functions. The resulting curves where fitted using the

Criteria Cleaning Effectiveness (E)

E Range	Utility Function
2.73 to 3.3	0.439 * E - 1.197
3.3 to 4.0	0.357 * E - 0.929
4.0 to 5.0	0.250 * E - 0.500
5.0 to 6.56	0.161 * E - 0.056

Criteria Cost (C)

C Range ($)	Utility Function
0.45 to 7.00	-0.0382 * C + 1.0172
7.00 to 12.00	-0.050 * C + 1.100
12.00 to 17.00	-0.050 * C + 1.100
17.00 to 21.37	-0.0572 * C + 1.222

Criteria Health/Safety Impact (HSI)

HSI Range	Utility Function
1.75 to 1.9	1.667 * HSI - 2.917
1.9 to 2.3	0.625 * HSI - 0.937
2.3 to 2.8	0.500 * HSI - 0.650
2.8 to 5.51	0.092 * HSI - 0.492

Criteria Environmental Impact (EI)

EI Range	Utility Function
1.84 to 2.1	0.962 * EI - 1.769
2.1 to 2.5	0.625 * EI - 1.062
2.5 to 3.0	0.500 * EI - 0.750
3.0 to 5.01	0.124 * EI + 0.377

Criteria Process Compatibility (PC)

PC Range	Utility Function
3.49 to 3.6	2.273 * PC - 7.932
3.6 to 3.8	1.250 * PC - 4.250
3.8 to 4.1	0.833 * PC - 2.665
4.1 to 5.25	0.217 * PC - 0.141

Table 13: Univariate Utility Functions

software package Statistix (version 4.0). Unfortunately, with the exception of the criteria cost, the curves were not adequately modeled using a third or second order polynomial (there were insufficient data points to apply more sophisticated methods). Given data constraints, a linear piecemeal approach was used to model the functions between the DM provided data points. The resulting equations are provided in Table 13. The alternative data can be translated from the attribute form provided in the expert criteria data table into utile values using the equations provided in Table 13. Plots of the univariate utility functions over the criteria ranges are provided in Appendix F. The figures also show the values provided directly from the survey section by the DM.

The complete MAUT data matrix with the normalized alternative criteria values expressed in utiles is provided as Table 14. These values may be input directly into the multiplicative utility function to provide the scoring of alternatives.

	Solvent Alternatives				
CRITERIA	Ardrox	Desoclean	Dynasolve	Metalube	PF 145 HP
Env. Impact	0.297	0.000	0.198	0.278	0.228
H/S Impact	0.298	0.000	0.233	0.270	0.200
Effectiveness	0.189	0.441	0.348	0.022	0.000
Process Com.	0.192	0.251	0.328	0.230	0.000
Cost	0.342	0.108	0.000	0.339	0.191

Table 14: MAUT Criteria Data Matrix (utiles)

MAUT Model Solution

Incorporating results from the four survey sections, the following multiplicative utility function is generated as discussed in Chapters 2 and 3.

$$U = (-1.014)\,[(-0.148U_{cost}+1)\,(-0.592U_{ei}+1)\,(-0.394U_{pc}+1)\,(-0.789U_{hsi}+1)\,(-0.692U_e+1)-1]$$

where U is the mutliplicative value function (utiles), U_c is the univariate utility function for cost, U_{ei} is the univariate utility function for environmental impact, U_{pc} is the univariate utility function for process compatibility, U_{hsi} is the univariate utility function for health/safety impact ,and U_e is the univariate utility function for effectiveness. Substituting the univariate utility function values listed in Table 14 into the above equation provides the alternative utility values (utiles) listed in Table 15.

Alternative	Ranking (Utiles)
Dynasolve	0.531
Ardrox	0.526
Metalube	0.447
Desoclean	0.389
PF 45 HP	0.296

Table 15: Ranking of Alternatives for MAUT Model

MAUT and AHP Model Comparison

There were significant differences in the difficulty/complexities involved in solving the models. The MAUT survey was difficult to administer due to the abstract nature of the questions and the requirements to establish preferential and utility independence. Additionally, the MAUT lottery questions used in Section 3 to determine univariate utility weights were confusing to the DM. The DM had a difficult time understanding the concepts involved in the survey with the exception of the last section. After explaining the concept of the lottery questions and the levels of outcomes resulting from the choices, the DM rescored his values in Section 3 of the survey. The DM had

little difficulty characterizing his univariate functions through the lottery techniques and certainty equivalence questions used in Section 4. This provided clear univariate functions which, by design, capture the DM's preference system. Note that the scales used only addressed the range of the alternative values which simplified the solution of the model. The actual analysis of the data and solving for multiplicative function parameters was straightforward.

The AHP model was easier to administer and solve using ExpertChoice. The only complaint from the DM concerned the 9 point scale used in the survey. The questions and concepts involved with the model were well understood by the DM. The model relies on the DM to transform attribute data to univariate function values through pairwise comparisons. Although the univariate functions are not specifically characterized through this process, the DM felt comfortable comparing the alternatives. The comparing of the criteria was difficult for the DM because the criteria were difficult to quantify in absolute terms (the functional forms of the criteria are not determined). The DM greatly preferred the AHP survey over the MAUT survey terms of complexity and data requirements.

Strategic Equivalence

The condition for strategic equivalence of two functions requires both functions to provide identical rankings of preferences over the entire range of attribute/criteria values. For this problem, the range for the criteria univariate value functions is 0 to 1.0. Given results from the models, the two functions are not equivalent. This is to be expected since the two methods use different criteria and univariate function assumptions. In particular, the AHP does not explicitly determine the DM's underlying univariate utility function.

In general however, the utility theory additive function may be strategically equivalent with the utility theory multiplicative form over a limited range of criteria values for specific univariate functions and scaling constants. To test for this, consider the two dimensional case with variables x and y, and an additive function (U_A) and multiplicative function (U_M) with the same univariate utility functions for x and y (denoted U_x and U_y for respectively). The two functions are defined $U_A = w_1\, U_x + w_2\, U_y$ and $U_M = k\, w_3\, w_4\, U_x\, U_y + w_3\, U_x + w_4\, U_y$.

As stated in Chapter 4, according to Seo and Sakawa (44:186-187), when U_A and U_M are strategically equivalent there exists constants $h(y^*)$ and $c(y^*)$ where

$$U_A(x, y^*) = h(y^*) + c(y^*)\, U_M(x, y^0).$$

Solving for the constant $h(y^*) = U_A(x^0, y^*) = w_2$. Substituting utility equations into the above equation and solving for $c(y^*)$ provides $c(y^*) = w_1 / w_3$. Solving the equation for $U_A(y, x^*)$ provides a constant $c(x^*) = w2 / w4$. Given this information, the functions may be strategically equivalent for cases involving alternatives with maximum attribute values y^* and/or x^*.

A graphical analysis of the problem illustrates the differences in the utility function curves. Given U_M and U_A values, the multivariate functions can be written and plotted in terms of U_2 and U_1. This provides the following two relationships;

$$(U_2)_M = (U_M - w_3 U_1) / (k w_3 w_4 U_1 + w_4)$$
$$(U_2)_A = (U_A - w_1 U_1) / w_2$$

The terms $(U_2)_M$ and $(U_2)_M$ denote the multiplicative and additive function forms respectively. Figure 4 shows the plot of these functions for $k = 2.5$, $w_3 = 0.3$, $w_4 = 0.4$,

$w_1 = 0.5$ and $w_2 = 0.5$ and for different U_M and U_A values. The plot illustrates the family of function shapes involved in the ranking of the alternatives using the two functions. Notice that the additive function has a constant slope, whereas the multiplicative function curves slightly depending on the U_1 and U_2 values. Consider two alternatives, one with $U_1 = 0.3$, $U_2 = 0.675$ and the other with $U_1 = 0.9$ and $U_2 = 0.15$. Using the additive function, alternative I is preferred over alternative II (U_A(I)=0.488, U_A(II)=0.525). Using the multiplicative function, alternative II is preferred over alternative I (U_M(I)=0.421, U_M(II)=0.375). As shown in Figure 4, this preference switch is due in part to the curving of the multiplicative function. Since the curve is directly related to the product $kw_3w_4U_1$, the analysis is intuitively justified (the multiplicative function mimics the additive function without the component).

Utility Function Plot

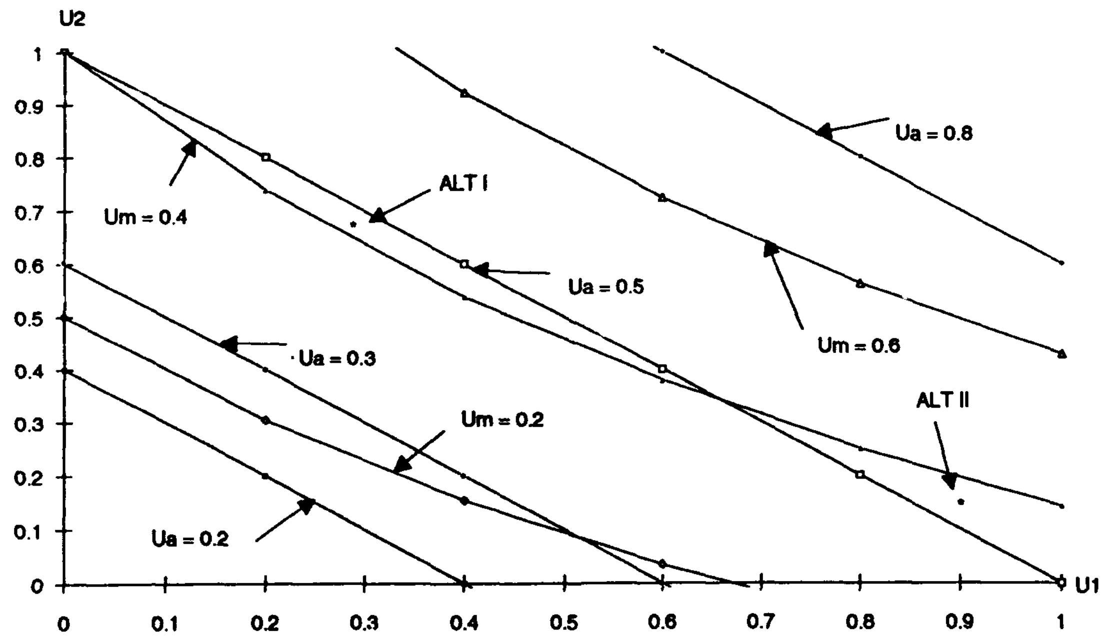


Figure 4: Two Variable Utility Function Plots

The slopes of the two functions $d(U_2)_M/dU_1$ and $d(U_2)_A/dU_1$ for constant U_M and U_A values provides the equations

$$d(U_2)_A/dU_1 = 1 - (1 / w_2)$$

$$d(U_2)_M/dU_1 = - w_3 / (k\, w_3\, w_4\, U_1 + w_4) + (w_3\, U_1 - U_M) / (k^2\, w_3^2\, w_4^2).$$

For simplicity, let [A] denote the term $d(U_2)_M/dU_1$.

Setting the slopes equal provides $w_2 = 1 / (1 - [A])$ and $w_1 = 1 - 1 /(1 - [A])$. Consider the sample case with w_1 and w_2 temporarily undefined. Letting $U_2 = 0.5$ and $U_1 = 0.3$ provides $[A] = - 3.334$. Solving for the weights provides $w_2 = 0.231$, $w_1 = 0.769$, and $U_A = 0.346$. This indicates that at the point $U_1 = 0.3$ and $U_2 = 0.5$ the multiplicative function has the same slope as an additive function with the weights determined above.

In general, the multiplicative function shape is different then the additive function shape due to the $kw_3w_4U_1U_2$ term. It is possible that multiplicative function shapes with relatively low $kw_3w_4U_1U_2$ values may have slopes approximately equaling linear additive function slopes over finite univariate ranges. But as shown above, the additive function weights which provide the same function shape slopes are dependent on the particular univariate U_1 and U_2 points in consideration.

Both U_A and U_M will provide preference of alternative I with $U_1 = x + \Delta x$ and $U_1 = y + \Delta y$ over alternative II with $U_1 = x$ and $U_2 = y$ for positive Δy and Δx since the U_1 and U_2 terms in both multivariate functions are positive (for positive k). Combining this information with the results from Seo and Sakawa provides the relationship that for n alternatives with m criteria and given criteria values

$$x_i(U_1, U_2, \ldots, U_m)\ ,\ x_j(U_1+\Delta x_1, U_2+\Delta y_1, \ldots, U_m+\Delta m_1), \ldots ,$$
$$x_j(U_1+\Delta x_n, U_2+\Delta y_n, \ldots, U_m+\Delta m_n)$$

where $0 >= \Delta x_1 >= \Delta x_2 \ldots >= \Delta x_n$ and $0 >= \Delta y_1 >= \Delta y_2 \ldots >= \Delta y_n$, the two functions U_A and U_M provide the same preference ranking and are strategically equivalent. In general however, the alternatives do not fit the above constraints and the functions may or not provide the same rankings depending on the specific scaling constants, weights and criteria ranges.

Given the above information, the two functions do not appear strategically equivalent. Additional research into the area is required to fully explore this issue. For purposes of this effort, substitution of the additive utility function for the more complex multiplicative function is unjustified.

As a last analysis of the additive utility function, the MAUT survey results were used to determine additive function weights as detailed in Chapter 3. The multiplicative weights determined by the MAUT survey were normalized to sum to 1. These weights were then used in the additive utility function. The resulting function is

$$U_A = 0.0566\ U_c + 0.226\ U_{ei} + 0.264\ U_e + 0.302\ U_{hsi} + 0.151\ U_{pc}$$

The criteria matrix values corresponding to the univariate functions developed for the multiplicative function were also used as the alternative univariate function values in the above equation.

Additionally, the MAUT criteria matrix values were input into the AHP model using the data entry mode of ExpertChoice. This explicitly captured the DM's univariate utility functions and scoring of the criteria weights. The ratios of the above additive

weight were also used for the AHP criteria comparisons. The resulting ranking from this and the above additive utility approach are depicted in Table 16. The results using the multiplicative and additive utility functions agree in terms of preference. The ratios of values which is a measure of the preference intensities do not match. The additive utility results exactly match the new AHP results. This is an important result because it indicates the AHP is strategically equivalent to the additive utility function if it can capture the DM's univariate utility preferences. For the test case involving the replacement of MEK, the resulting AHP and additive utility rankings do not agree.

	U_M	U_A	AHP[1]	AHP[2]
Dynasolve	0.531	0.257	0.257	0.200
Ardrox	0.526	0.255	0.255	0.268
Metalube	0.447	0.204	0.203	0.228
Desoclean	0.389	0.160	0.163	0.152
PF 145 HP	0.296	0.123	0.122	0.152

1 - AHP results using the utility function data and weights.
2 - original AHP results using data prepared by DM.

Table 16: Modified MAUT and AHP Model Results

Therefore, either the original AHP comparisons did not capture the DM's preferences or the MAUT survey failed to provide the univariate utility functions, or both.

Verification and Validation

As mentioned earlier, the weights for the criteria resulting from the MAUT Section 3 were not consistent with the rankings used in the AHP survey. The DM reversed the importance of several criteria between the two methods which was immediately evident by his survey answers. This identified a potential problem with the

survey questions. After discussing the issue with the DM, I learned that he was incorrectly assuming that alternative criteria values of 0 represented unacceptable substitutes. The DM was carefully assured that all of the alternatives being considered met minimum replacement requirements and were capable of replacing MEK for this application. The DM rescored the weights determined in MAUT survey Section 3. The new results corrected the original inconsistency.

Results from both of models were presented to the DM. Given his high emphasis on the criteria health/safety impact and effectiveness, the DM had little difficulty agreeing to the ranking of Ardrox as the preferred alternative (original AHP choice).

As a verification check on the expert team's input, the DM also evaluated the factor data and generated a ranking of the alternative criteria values. The results are provided in Table 17.

	Solvent Alternatives				
CRITERIA	Ardrox	Desoclean	Dynasolve	Metalube	PF 145 HP
Env. Impact	6	2	5	7	3
H/S Impact	6	2	5	7	3
Effectiveness	4	6	5	3	2
Process Com.	3	7	6	4	2

(Cost was not evaluated at this level by either the Decision Maker or expert team)

Table 17: Decision Maker's Criteria Matrix

The results compare to the data generated by the expert team with the exception of Metalube and Desoclean. The DM scored Metalube several points higher then the team for both environmental impact and health/safety impact. He also scored Desoclean several points higher for process compatibility. The discrepancy may result from the DM's knowledge of manufacturing processes involving aqueous substitutes (like

Metalube) for solvent based cleaners (like Desoclean). The DM also answered AHP survey questions using the Table 17 data set. The resulting AHP rankings differ from earlier results in that Metalube has the highest ranking, followed by Ardrox. The increase in the Metalube and Desoclean scores account for the differences. Results are presented in Table 18.

	MAUT	AHP[1]	AHP[2]
Ardrox	0.526	0.267	0.237
Metalube	0.447	0.228	0.252
Dynasolve	0.531	0.203	0.236
Desoclean	0.389	0.146	0.156
PF 145 HP	0.296	0.157	0.119

1 - AHP results using data prepared by the expert team.
2 - AHP results using data prepared by DM.

Table 18: Modified MAUT and AHP Model Results

The DM accepted the results of the AHP model including the ranking of the preferences. He is less comfortable with the MAUT results because of his uncertainties regarding survey question interpretations. He stressed the need to quantify the criteria including identification of the factors which impact them.

Chapter 5

Conclusions and Recommendations

The purpose of this chapter is to summarize the conclusions of the research and present recommendations for continued research. The research identified successfully met objectives within the confines set forth in Chapter One.

Conclusions

Specific conclusions of the research are as follows:

1. Factors have been identified which impact wipe solvent substitution decisions. The factors should be quantified to provide decision makers with information required to determine criteria values for alternatives.

2. The Analytical Hierarchical Process provides a management tool capable of resolving solvent substitution decisions involving complex criteria and alternatives. The model provides ranking of alternatives without specifically determining univariate utility or value functions. It is easier to use then conventional utility theory techniques.

3. Multiattribute utility theory provides a management tool capable of resolving solvent substitution decisions involving complex criteria and alternatives. Although it specifically captures the decision maker's preferences on criteria functions, it is difficult to implement due to complexities in establishing the scaling values using conventional lottery techniques.

4. For specific decision problem conditions, the Analytical Hierarchical Process and Utility Theory Models may not provide identical preference rankings of alternatives. If the utility theory univariate utility functions are captured and input into AHP, the model provides the same rankings as an additive utility model.

5. Clear definition of terms, especially criteria, is vital to obtaining accurate results using the Analytical Hierarchical Process and Utility Theory models. The issue is more evident in utility theory due to the lottery techniques used to develop univariate utility functions (lottery techniques require comparisons of criteria at low and high conditions versus sure outcomes at specified levels).

6. Given constraints on the univariate criteria values of alternatives, the multiplicative function and the additive function are strategically equivalent. Ranges of criteria outside the constraints may or may not allow for equivalency of functions, depending on function parameters.

7. The use of Utility Theory involves verification of independence requirements which may be difficult to establish given several attributes/criteria which are difficult to quantify.

8. The Analytical Hierarchical Process recommends a nine point scale which may present concern among decision makers who are reluctant to place twice or higher importance levels one criteria over another.

Recommendations

Recommendations for continued research are;

1. Additional research is required to identify specific test methods for quantifying the criteria factors. This will provide a useful tool for comparing alternatives by establishing common test procedures and data requirements provided by solvent manufacturers.

2. Research into combining the two methods may provide a useful tool which accurately captures the decision maker's preferences through utility theory and uses the Analytical Hierarchical Process to determine weights through normalized eigenvector summation techniques.

3. Research into the comparison of the utility theory additive functions and the representation of additive preferences using Wakker's techniques may provide an additional tool for capturing preferences without the need for lottery techniques.

4. Research into the use of interactive techniques may further define the alternative attribute ranges prior to surveying DMs. This may help reduce the data demands required by the AHP and MAUT models.

APPENDIX A

EXPERT TEAM SOLVENT DATA SURVEY

COVER LETTER, SOLVENT DATA, AND SURVEY QUESTIONAIRE

MEMORANDUM FOR SOLVENT PROJECT TEAM 17 Jun 94

FROM: AFIT/ENV
2950 P Street
Wright Patterson AFB OH 45433-7765

SUBJECT: Request for information on solvent attributes

1. As part of my thesis project at the Air Force Institute of Technology, I am developing a management decision model for evaluating hazardous solvent replacement alternatives. I am using an actual field solvent replacement effort to identify pertinent model criteria. As discussed in our previous telephone conversations, I would appreciate your help in establishing solvent attributes for the model. Specifically, I need you to help me score the alternatives and identify criteria functions. The entire effort will only require a few minutes of your time. Please note that this project and any information you provide will be used strictly for educational purposes.

2. The test case involves the replacement of methyl ethyl ketone used to clean dry film lubricant from titanium blades (Ti-64) prior to inspection. The lubricant is later reapplied and baked on. There are five solvent choices, each meeting minimum requirements. Data on the characteristics of the solvents is provided, including test data on cleaning effectiveness. For simplicity, consider the soils used during cleaning testing to reflect materials encountered during the actual cleaning operation. The percent by weight constituents of the solvents are also provided.

3. On the criteria data sheet, please score the solvent attribute value for each criteria on a scale between 1 and 7 based upon the provided data. Note that two or more solvents may have the same criteria value if you choose. On the criteria function sheet, please list the attributes you think are critical to the individual criteria. Specific instructions are provided.

4. I greatly appreciate your help with this project and look forward to reviewing your input. I will contact you in a few days to address any concerns you may have.

Jaimie S. Tiley, P.E.
Student, Department of Engineering
and Environmental Management

Attachments:
1. Solvent Data
2. Criteria Forms

Solvent Data

	Ardrox 180 BH	Desoclean 45	Dynasolve 108	Metalube 4U	PF145 HP
Flashpoint (deg F):	>200	22	155	----	145
Evaporation Rates					
cleaner/water:	0.66	5.52	0.64	0.74	0.2
cleaner/butylacetate:	1	<1	----	<1	----
Vapor Press. (mm Hg):	17	3	3	17	<1
Non Volatile Residue (g/l):	10725	45	1262	69	30069
VOC (g/l):	53	784	948	57	850
Odor:	mild	unpleasant	strong	mint	unpleasant
Cleaner Type:	aqueous	solvent	blend	aqueous	hydrocarb

Cleaning Results: (wiping test coupons)	**73X Marking Ink**	**Blue Layout Dye**	**Apiezon Grease**	**Carbo Wax**
Ardrox 180 BH:	A	A	B	C
Desoclean 45:	A	B	A	A
Dynasolve 108:	A	A	B	B
Metalube 4U:	A	A	C	D
PF 145 HP:	D	D	A	A

(a = excellent/minimal wiping, b = good/moderate wiping, c = average/heavy wiping, d = poor/heavy wiping (may not work))

Solvent Ingredients:

(Note: TLV and or PEL values in parenthesis if applicable)

Ardrox 180 BH

Water 84.5%
NVR 10.5%
Ethylene Glycol Butyl Ether 4.7%
Diethylene Gylcol Butyl Ether 0.2%

Metalube 4U

Water 78.7%
NVR 15.5%
Diethylene Glycol Butyl Ether 5.3%
Hexamethyl Cyclotnsiloxane 0.5%
(100 ppm)

Desoclean 45

Methyl Ethyl Ketone 37.79%	(200 ppm)
Isopropanol 27.7%	(400 ppm)
Toluene 21.5%	(100 ppm)
Methyl Isobutyl Ketone 7.9%	(50 ppm)
Xylene 0.2%	(100 ppm)
NVR 0.1%	

Dynasolve 108

Ethyl S-hydroxy Propionate 69.18%
C_9-C_{11} Paraffinic Hydrocarbon 15.1%
(300 ppm*)
Propoxypropanol 14.8%
3-Methoxy 3-Methyl 2-Butanone 0.4%
Water 0.2%
NVR 0.02%

PF 145 HP

C_9-C_{11} Aromatic Hydrocarbon 76.99%
C_9-C_{11} Paraffinic Hydrocarbon 23.0% (300 ppm*)
NVR 0.01%

NVR = non-volatile residue
* recommended by manufacturer

Task 1: Criteria Data Sheet

(Criteria, 7 point scale, more is better...)

Criteria1: Environmental Impact 1=Negative Impact, 7=Good Impact		Criteria 2: Health/Safety Impact 1=Negative Impact, 7=Good Impact
Ardrox 180 BH:	_____	_____
Desoclean 45:	_____	_____
Dynasolve 108:	_____	_____
Metalube 4U:	_____	_____
PF 145 HP:	_____	_____

Criteria 3: Process Compatibility 1=Very Uncompatible, 7=Very Compatible		Criteria 4: Cleaning Effectiveness 1=Very Ineffective, 7=Very Effective
Ardrox 180 BH:	_____	_____
Desoclean 45:	_____	_____
Dynasolve 108:	_____	_____
Metalube 4U:	_____	_____
PF 145 HP:	_____	_____

Task 2: Criteria Attribute Functions

Consider the following solvent attributes:

biodegradibility	17 industrial toxin lists
toxicity	PEL/TLV
vapor pressure	safety equipment requirements
evaporation rate	explosiveness
non volatile residue	ignitability
volatile organic carbon content	reactivity
odor	disposal costs
hazardous constituents	purchase costs
cleaning time required	scrubbing effort required
cleaning effectiveness	ozone depleting substance characteristics
startup time requirements	training requirements
permitting requirements	startup equipment purchase requirements

Now consider which ones impact the criteria. For example, consider Environmental Impact. I think Environmental Impact is a function of the following attributes:

biodegradability
toxicity
ODS characteristics
RCRA characteristics, etc.

Please list which attributes are important to the specific criteria as written below. Feel free to include attributes not listed above, the list is only meant as a reference.

<u>Environmental Impact</u> <u>Health/Safety Impact</u> <u>Effectiveness</u> <u>Process</u> <u>Compatibility</u>

APPENDIX B

ANALYTICAL HEIRARCHICAL PROCESS SURVEY

Node: 0

Compare the relative PREFERENCE with respect to: GOAL

Circle one number per comparison below using the scale:
1=EQUAL 3=MODERATE 5=STRONG 7=VERY STRONG 9=EXTREME

1	COST	9 8 7 6 5 4 3 2	1	2 3 4 5 6 7 8 9	EFF.
2	COST	9 8 7 6 5 4 3 2	1	2 3 4 5 6 7 8 9	PROC COM
3	COST	9 8 7 6 5 4 3 2	1	2 3 4 5 6 7 8 9	E IMPACT
4	COST	9 8 7 6 5 4 3 2	1	2 3 4 5 6 7 8 9	H IMPACT
5	EFF.	9 8 7 6 5 4 3 2	1	2 3 4 5 6 7 8 9	PROC COM
6	EFF.	9 8 7 6 5 4 3 2	1	2 3 4 5 6 7 8 9	E IMPACT
7	EFF.	9 8 7 6 5 4 3 2	1	2 3 4 5 6 7 8 9	H IMPACT
8	PROC COM	9 8 7 6 5 4 3 2	1	2 3 4 5 6 7 8 9	E IMPACT
9	PROC COM	9 8 7 6 5 4 3 2	1	2 3 4 5 6 7 8 9	H IMPACT
10	E IMPACT	9 8 7 6 5 4 3 2	1	2 3 4 5 6 7 8 9	H IMPACT

GOAL: CHOOSE BEST SOLVENT ALTERNATIVE

:OST --- COST OF SOLVENT
: IMPACT --- ENVIRONMENTAL IMPACT
:FF. --- CLEANING EFFECTIVENESS
I IMPACT --- HEALTH/SAFETY IMPACT
PROC COM --- PROCESS COMPATIBILITY

Node: 50000

Compare the relative PREFERENCE with respect to: H IMPACT < GOAL

Circle one number per comparison below using the scale:
1=EQUAL 3=MODERATE 5=STRONG 7=VERY STRONG 9=EXTREME

1	DYNASOLV	9 8 7 6 5 4 3 2	1	2 3 4 5 6 7 8 9	MC509-4U
2	DYNASOLV	9 8 7 6 5 4 3 2	1	2 3 4 5 6 7 8 9	DESO 45
3	DYNASOLV	9 8 7 6 5 4 3 2	1	2 3 4 5 6 7 8 9	ARDROX
4	DYNASOLV	9 8 7 6 5 4 3 2	1	2 3 4 5 6 7 8 9	PF 145
5	MC509-4U	9 8 7 6 5 4 3 2	1	2 3 4 5 6 7 8 9	DESO 45
6	MC509-4U	9 8 7 6 5 4 3 2	1	2 3 4 5 6 7 8 9	ARDROX
7	MC509-4U	9 8 7 6 5 4 3 2	1	2 3 4 5 6 7 8 9	PF 145
8	DESO 45	9 8 7 6 5 4 3 2	1	2 3 4 5 6 7 8 9	ARDROX
9	DESO 45	9 8 7 6 5 4 3 2	1	2 3 4 5 6 7 8 9	PF 145
10	ARDROX	9 8 7 6 5 4 3 2	1	2 3 4 5 6 7 8 9	PF 145

GOAL: CHOOSE BEST SOLVENT ALTERNATIVE

ARDROX --- ARDROX 180 BH
DESO 45 --- DESOCLEAN 45
DYNASOLV --- DYNASOLVE 108
H IMPACT --- HEALTH/SAFETY IMPACT
MC509-4U --- METALUBE MC509-4U
PF 145 --- PF 145

Node: 10000

Compare the relative PREFERENCE with respect to: COST < GOAL

Circle one number per comparison below using the scale:
1=EQUAL 3=MODERATE 5=STRONG 7=VERY STRONG 9=EXTREME

1	DYNASOLV	9 8 7 6 5 4 3 2	1	2 3 4 5 6 7 8 9	MC509-4U
2	DYNASOLV	9 8 7 6 5 4 3 2	1	2 3 4 5 6 7 8 9	DESO 45
3	DYNASOLV	9 8 7 6 5 4 3 2	1	2 3 4 5 6 7 8 9	ARDROX
4	DYNASOLV	9 8 7 6 5 4 3 2	1	2 3 4 5 6 7 8 9	PF 145
5	MC509-4U	9 8 7 6 5 4 3 2	1	2 3 4 5 6 7 8 ~~9~~	DESO 45
6	MC509-4U	9 8 7 6 5 4 3 2	1	2 3 4 5 6 7 8 9	ARDROX
7	MC509-4U	9 8 7 6 5 4 3 2	1	2 3 4 5 6 7 8 9	PF 145
8	DESO 45	9 8 7 6 5 4 3 2	1	2 3 4 5 6 7 8 9	ARDROX
9	DESO 45	9 8 7 6 5 4 3 2	1	2 3 4 5 6 7 8 9	PF 145
10	ARDROX	9 8 7 6 5 4 3 2	1	2 3 4 5 6 7 8 9	PF 145

GOAL: CHOOSE BEST SOLVENT ALTERNATIVE

ARDROX --- ARDROX 180 BH
COST --- COST OF SOLVENT
DESO 45 --- DESOCLEAN 45
DYNASOLV --- DYNASOLVE 108
MC509-4U --- METALUBE MC509-4U
PF 145 --- PF 145

Node: 20000

Compare the relative PREFERENCE with respect to: EFF. < GOAL

Circle one number per comparison below using the scale:
1=EQUAL 3=MODERATE 5=STRONG 7=VERY STRONG 9=EXTREME

1	DYNASOLV	9 8 7 6 5 4 3 2	1	2 3 4 5 6 7 8 9	MC509-4U
2	DYNASOLV	9 8 7 6 5 4 3 2	1	2 3 4 5 6 7 8 9	DESO 45
3	DYNASOLV	9 8 7 6 5 4 3 2	1	2 3 4 5 6 7 8 9	ARDROX
4	DYNASOLV	9 8 7 6 5 4 3 2	1	2 3 4 5 6 7 8 9	PF 145
5	MC509-4U	9 8 7 6 5 4 3 2	1	2 3 4 5 6 7 8 9	DESO 45
6	MC509-4U	9 8 7 6 5 4 3 2	1	2 3 4 5 6 7 8 9	ARDROX
7	MC509-4U	9 8 7 6 5 4 3 2	1	2 3 4 5 6 7 8 9	PF 145
8	DESO 45	9 8 7 6 5 4 3 2	1	2 3 4 5 6 7 8 9	ARDROX
9	DESO 45	9 8 7 6 5 4 3 2	1	2 3 4 5 6 7 8 9	PF 145
10	ARDROX	9 8 7 6 5 4 3 2	1	2 3 4 5 6 7 8 9	PF 145

GOAL: CHOOSE BEST SOLVENT ALTERNATIVE

ARDROX --- ARDROX 180 BH
DESO 45 --- DESOCLEAN 45
DYNASOLV --- DYNASOLVE 108
EFF. --- CLEANING EFFECTIVENESS
MC509-4U --- METALUBE MC509-4U
PF 145 --- PF 145

Node: 30000

Compare the relative PREFERENCE with respect to: PROC COM < GOAL

Circle one number per comparison below using the scale:
1=EQUAL 3=MODERATE 5=STRONG 7=VERY STRONG 9=EXTREME

1	DYNASOLV	9 8 7 6 5 4 3 2	1	2 3 4 5 6 7 8 9	MC509-4U
2	DYNASOLV	9 8 7 6 5 4 3 2	1	2 3 4 5 6 7 8 9	DESO 45
3	DYNASOLV	9 8 7 6 5 4 3 2	1	2 3 4 5 6 7 8 9	ARDROX
4	DYNASOLV	9 8 7 6 5 4 3 2	1	2 3 4 5 6 7 8 9	PF 145
5	MC509-4U	9 8 7 6 5 4 3 2	1	2 3 4 5 6 7 8 9	DESO 45
6	MC509-4U	9 8 7 6 5 4 3 2	1	2 3 4 5 6 7 8 9	ARDROX
7	MC509-4U	9 8 7 6 5 4 3 2	1	2 3 4 5 6 7 8 9	PF 145
8	DESO 45	9 8 7 6 5 4 3 2	1	2 3 4 5 6 7 8 9	ARDROX
9	DESO 45	9 8 7 6 5 4 3 2	1	2 3 4 5 6 7 8 9	PF 145
10	ARDROX	9 8 7 6 5 4 3 2	1	2 3 4 5 6 7 8 9	PF 145

GOAL: CHOOSE BEST SOLVENT ALTERNATIVE

ARDROX --- ARDROX 180 BH
DESO 45 --- DESOCLEAN 45
DYNASOLV --- DYNASOLVE 108
MC509-4U --- METALUBE MC509-4U
PF 145 --- PF 145
PROC COM --- PROCESS COMPATIBILITY

Node: 40000

Compare the relative PREFERENCE with respect to: E IMPACT < GOAL

Circle one number per comparison below using the scale:
1=EQUAL 3=MODERATE 5=STRONG 7=VERY STRONG 9=EXTREME

1	DYNASOLV	9 8 7 6 5 4 3 2	1	2 3 4 5 6 7 8 9	MC509-4U
2	DYNASOLV	9 8 7 6 5 4 3 2	1	2 3 4 5 6 7 8 9	DESO 45
3	DYNASOLV	9 8 7 6 5 4 3 2	1	2 3 4 5 6 7 8 9	ARDROX
4	DYNASOLV	9 8 7 6 5 4 3 2	1	2 3 4 5 6 7 8 9	PF 145
5	MC509-4U	9 8 7 6 5 4 3 2	1	2 3 4 5 6 7 8 9	DESO 45
6	MC509-4U	9 8 7 6 5 4 3 2	1	2 3 4 5 6 7 8 9	ARDROX
7	MC509-4U	9 8 7 6 5 4 3 2	1	2 3 4 5 6 7 8 9	PF 145
8	DESO 45	9 8 7 6 5 4 3 2	1	2 3 4 5 6 7 8 9	ARDROX
9	DESO 45	9 8 7 6 5 4 3 2	1	2 3 4 5 6 7 8 9	PF 145
10	ARDROX	9 8 7 6 5 4 3 2	1	2 3 4 5 6 7 8 9	PF 145

GOAL: CHOOSE BEST SOLVENT ALTERNATIVE

ARDROX --- ARDROX 180 BH
DESO 45 --- DESOCLEAN 45
DYNASOLV --- DYNASOLVE 108
E IMPACT --- ENVIRONMENTAL IMPACT
MC509-4U --- METALUBE MC509-4U
PF 145 --- PF 145

Appendix C: MAUT Survey

Section One: Preferential Independence

Please answer the following set of questions...

1. a. Two solvents have the same environmental impact, health/safety impact, process compatibility and effectiveness values of 1 out of a 7 point scale (7 is better). Which solvent is preferred, solvent A which has a cost of 45 cents, or solvent B which has a cost of $ 21.37?

A or B

b. Now, consider two solvents which have the same environmental impact, health/safety impact, process compatibility and values of 1 out of a 7 point scale (7 is better), but effectiveness values of 7. Which solvent is preferred, solvent A which has a cost of 45 cents, or solvent B which has a cost of $ 21.37?

A or B

c. Now, consider two solvents which have the same environmental impact, health/safety impact and effectiveness values of 1 out of a 7 point scale (7 is better), but process compatibility values of 7. Which solvent is preferred, solvent A which has a cost of 45 cents, or solvent B which has a cost of $ 21.37?

A or B

d. Now, consider two solvents which have the same environmental impact, effectiveness and process compatibility values of 1 out of a 7 point scale (7 is better), but health/safety impact values of 7. Which solvent is preferred, solvent A which has a cost of 45 cents, or solvent B which has a cost of $ 21.37?

A or B

e. Now, consider two solvents which have the same health/safety impact, effectiveness, and process compatibility values of 1 out of a 7 point scale (7 is better), but

environmental impact values of 7. Which solvent is preferred, solvent A which has a cost of 45 cents, or solvent B which has a cost of $ 21.37?

A **or** **B**

2. a. Now, consider two solvents which have the same cost of $ 0.45, and environmental impact, health/safety impact and effectiveness values of 1 out of a 7 point scale (7 is better). Which solvent is preferred, solvent A which has a process compatibility value of 1, or solvent B which has a process compatibility value of 7?

A **or** **B**

b. Now, consider two solvents which have the same cost of $ 0.45, and environmental impact, health/safety impact values of 1 out of a 7 point scale (7 is better), but effectiveness values of 7. Which solvent is preferred, solvent A which has a process compatibility value of 1, or solvent B which has a process compatibility value of 7?

A **or** **B**

c. Now, consider two solvents which have the same cost of $ 0.45, and environmental impact, and effectiveness values of 1 out of a 7 point scale (7 is better), but health/safety impacts values of 7. Which solvent is preferred, solvent A which has a process compatibility value of 1, or solvent B which has a process compatibility value of 7?

A **or** **B**

d. Now, consider two solvents which have the same cost of $ 0.45, and health/safety impact and effectiveness values of 1 out of a 7 point scale (7 is better), but environmental impact values of 7. Which solvent is preferred, solvent A which has a process compatibility value of 1, or solvent B which has a process compatibility value of 7?

A **or** **B**

e. Now, consider two solvents which have the same environmental impact, health/safety impact and effectiveness values of 1 out of a 7 point scale (7 is better). Both cost $ 21.37. Which solvent is preferred, solvent A which has a process compatibility value of 1, or solvent B which has a process compatibility value of 7?

A **or** **B**

3. a. Now, consider two solvents which have the same cost of $ 0.45, and environmental impact, health/safety impact and process compatibility values of 1 out of a 7 point scale (7 is better). Which solvent is preferred, solvent A which has an effectiveness value of 1, or solvent B which has an effectiveness value of 7?

A or B

b. Now, consider two solvents which have the same cost of $ 0.45, and environmental impact, health/safety impact values of 1 out of a 7 point scale (7 is better), but process compatibility values of 7. Which solvent is preferred, solvent A which has an effectiveness value of 1, or solvent B which has an effectiveness value of 7?

A or B

c. Now, consider two solvents which have the same cost of $ 0.45, and environmental impact, process compatibility values of 1 out of a 7 point scale (7 is better), but health/safety impact values of 7. Which solvent is preferred, solvent A which has an effectiveness value of 1, or solvent B which has an effectiveness value of 7?

A or B

d. Now, consider two solvents which have the same cost of $ 0.45, and process compatibility, health/safety impact values of 1 out of a 7 point scale (7 is better), but environmental impact values of 7. Which solvent is preferred, solvent A which has an effectiveness value of 1, or solvent B which has an effectiveness value of 7?

A or B

e. Now, consider two solvents which have the same environmental impact, health/safety impact, and process compatibility values of 1 out of a 7 point scale (7 is better), but cost $ 21.37. Which solvent is preferred, solvent A which has an effectiveness value of 1, or solvent B which has an effectiveness value of 7?

A or B

4. a. Now, consider two solvents which have the same cost of $ 0.45, and environmental impact, effectiveness and process compatibility values of 1 out of a 7 point scale (7 is

better). Which solvent is preferred, solvent A which has a health/safety impact value of 1, or solvent B which has a health/safety impact value of 7?

A or B

b. Now, consider two solvents which have the same cost of $ 0.45, and environmental impact, and effectiveness values of 1 out of a 7 point scale (7 is better), but process compatibility values of 7. Which solvent is preferred, solvent A which has a health/safety impact value of 1, or solvent B which has a health/safety impact value of 7?

A or B

c. Now, consider two solvents which have the same cost of $ 0.45, and environmental impact, and process compatibility values of 1 out of a 7 point scale (7 is better), but effectiveness values of 7. Which solvent is preferred, solvent A which has a health/safety impact value of 1, or solvent B which has a health/safety impact value of 7?

A or B

d. Now, consider two solvents which have the same cost of $ 0.45, effectiveness, and process compatibility values of 1 out of a 7 point scale (7 is better), but environmental impact values of 7. Which solvent is preferred, solvent A which has a health/safety impact value of 1, or solvent B which has a health/safety impact value of 7?

A or B

e. Now, consider two solvents which have the same environmental impact, effectiveness and process compatibility values of 1 out of a 7 point scale (7 is better), but cost $ 21.37. Which solvent is preferred, solvent A which has a health/safety impact value of 1, or solvent B which has a health/safety impact value of 7?

A or B

5. a. Now, consider two solvents which have the same cost of $ 0.45, health/safety impact, effectiveness and process compatibility values of 1 out of a 7 point scale (7 is

better). Which solvent is preferred, solvent A which has a environmental impact value of 1, or solvent B which has an environmental impact value of 7?

A **or** **B**

b. Now, consider two solvents which have the same cost of $ 0.45, health/safety impact, and effectiveness values of 1 out of a 7 point scale (7 is better), but process compatibility values of 7. Which solvent is preferred, solvent A which has an environmental impact value of 1, or solvent B which has an environmental impact value of 7?

A **or** **B**

c. Now, consider two solvents which have the same cost of $ 0.45, health/safety impact, and process compatibility values of 1 out of a 7 point scale (7 is better), but effectiveness values of 7. Which solvent is preferred, solvent A which has an environmental impact value of 1, or solvent B which has an environmental impact value of 7?

A **or** **B**

d. Now, consider two solvents which have the same cost of $ 0.45, effectiveness, and process compatibility values of 1 out of a 7 point scale (7 is better), but health/safety impact values of 7. Which solvent is preferred, solvent A which has an environmental impact value of 1, or solvent B which has an environmental impact value of 7?

A **or** **B**

e. Now, consider two solvents which have the same health/safety impact, effectiveness and process compatibility values of 1 out of a 7 point scale (7 is better), but cost $ 21.37. Which solvent is preferred, solvent A which has an environmental impact value of 1, or solvent B which has an environmental impact value of 7?

A **or** **B**

This completes section one.

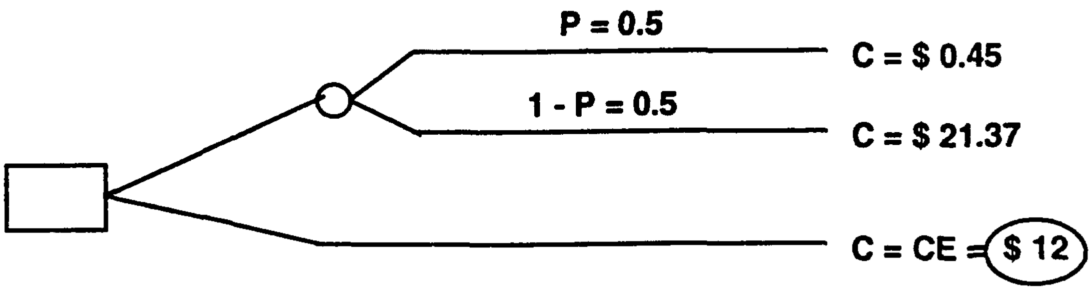
MAUT Survey

Section Two: Utility Independence

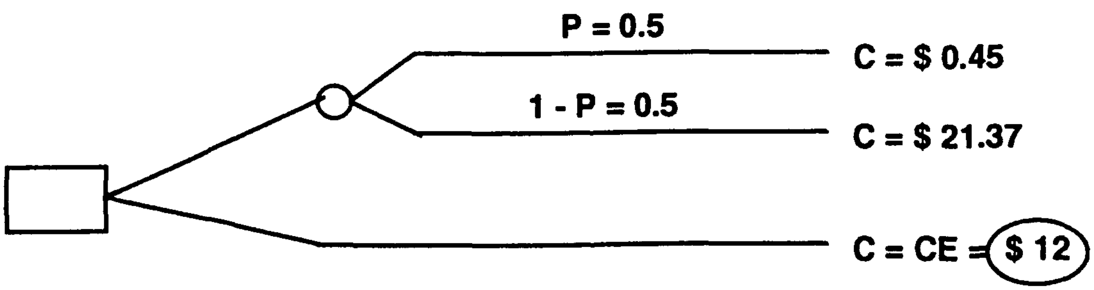
Please answer the following set of questions...

Consider the decisions below where you have a choice between a lottery result and a sure value (denoted CE). What value for CE would you be indifferent between the lottery and the sure thing? (The probability value is denoted P)

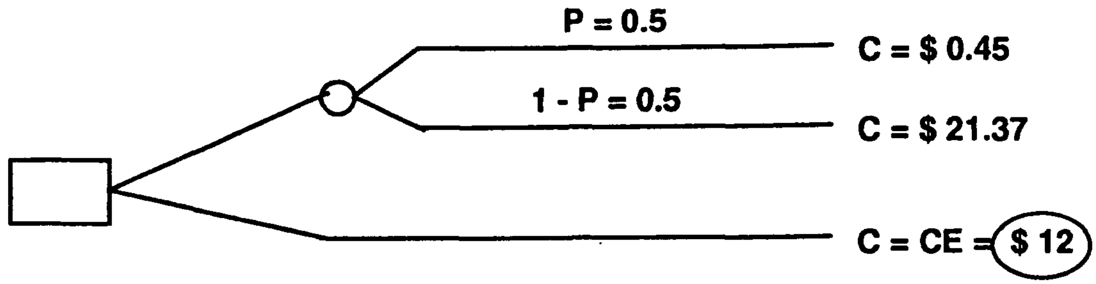
1. a. A solvent has environmental impact, health/safety impact, process compatibility and effectiveness values of 1 out of a 7 point scale (7 is better). What value of CE would you choose?



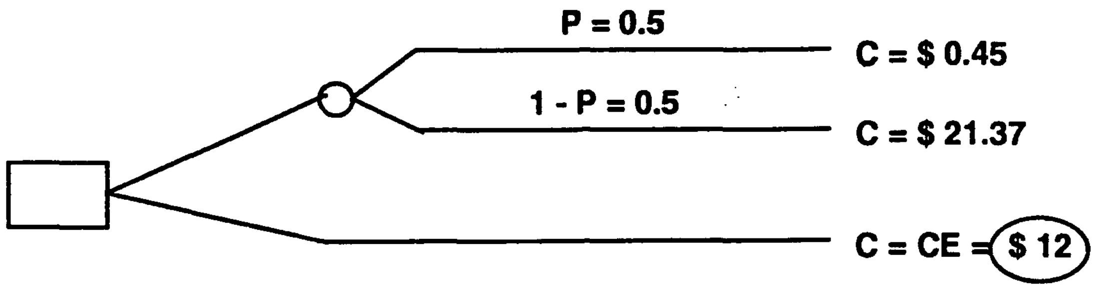
b. Now consider the solvents has environmental impact, health/safety impact, process compatibility and values of 1 out of a 7 point scale (7 is better), but an effectiveness value of 7. What value of CE would you choose?



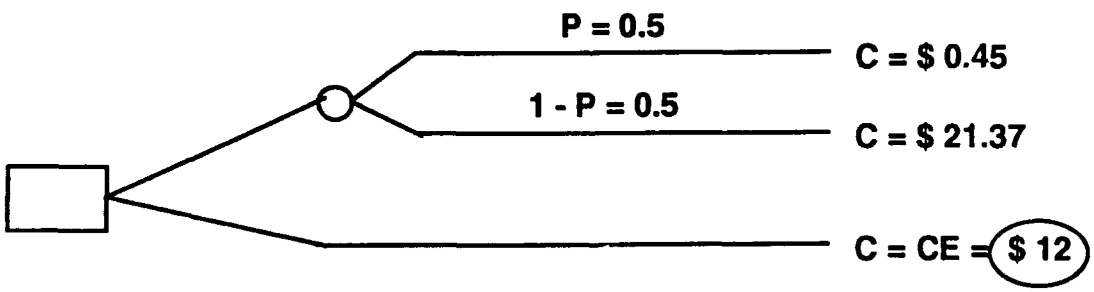
c. Now consider the solvent has environmental impact, health/safety impact and effectiveness values of 1 out of a 7 point scale (7 is better), but a process compatibility value of 7. What value of CE would you choose?



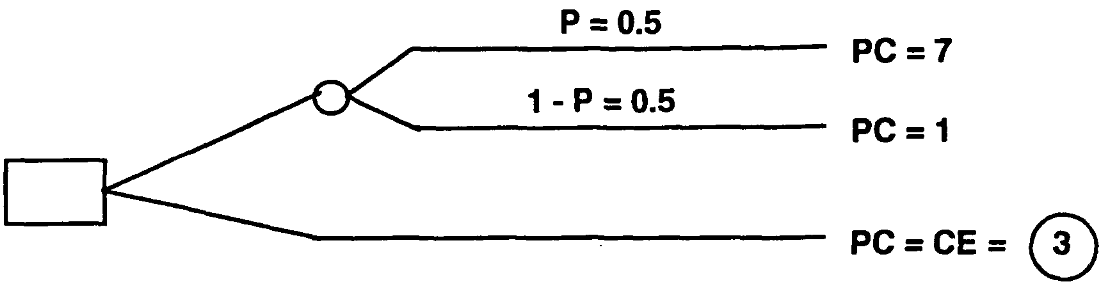
d. Now, consider the solvent has environmental impact, effectiveness and process compatibility values of 1 out of a 7 point scale (7 is better), but a health/safety impact value of 7. What value of CE would you choose?



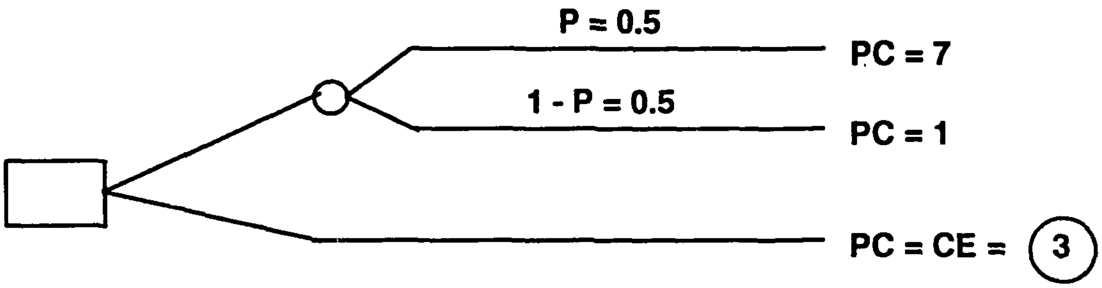
e. Now, consider the solvent has health/safety impact, effectiveness, and process compatibility values of 1 out of a 7 point scale (7 is better), but an environmental impact value of 7. What CE value would you choose?



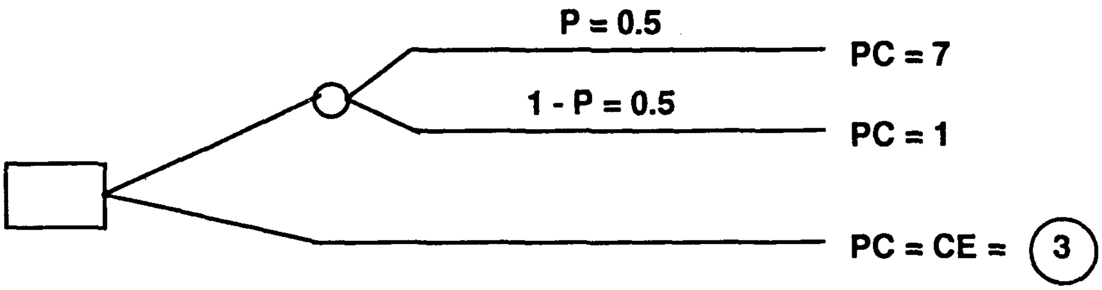
2. a. Now, consider the solvent has a cost of $ 0.45, and environmental impact, and health/safety impact and effectiveness values of 1 out of a 7 point scale (7 is better). What value of CE would you choose?



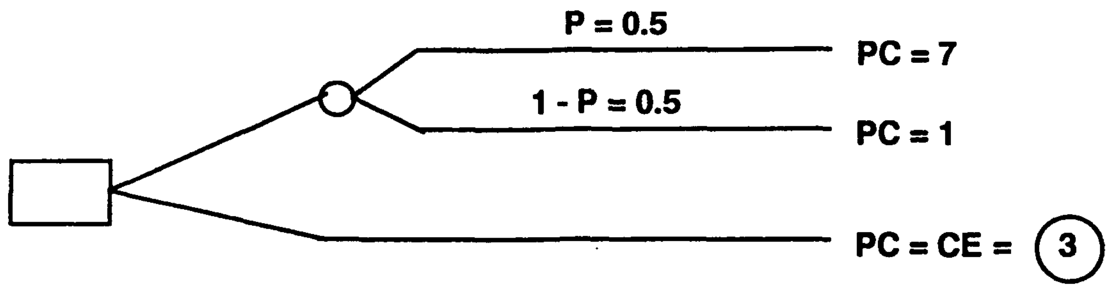
b. Now, consider the solvent has a cost of \$ 0.45, and environmental impact, health/safety impact values of 1 out of a 7 point scale (7 is better), but an effectiveness value of 7. What value of CE would you choose?



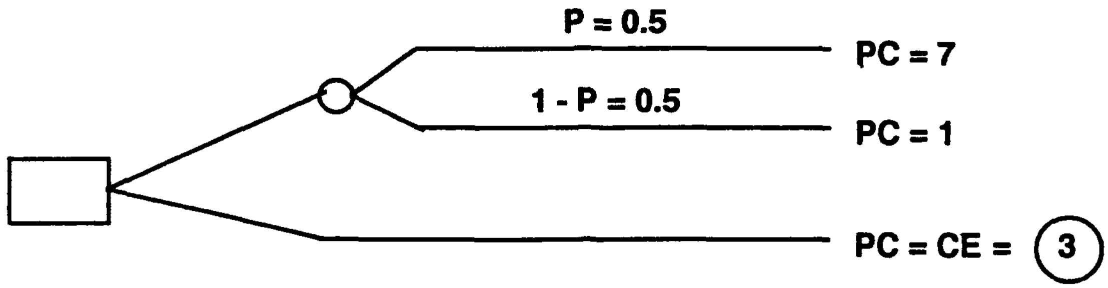
c. Now, consider the solvent has a cost of \$ 0.45, and environmental impact, and effectiveness values of 1 out of a 7 point scale (7 is better), but a health/safety impact value of 7. What value of CE would you choose?



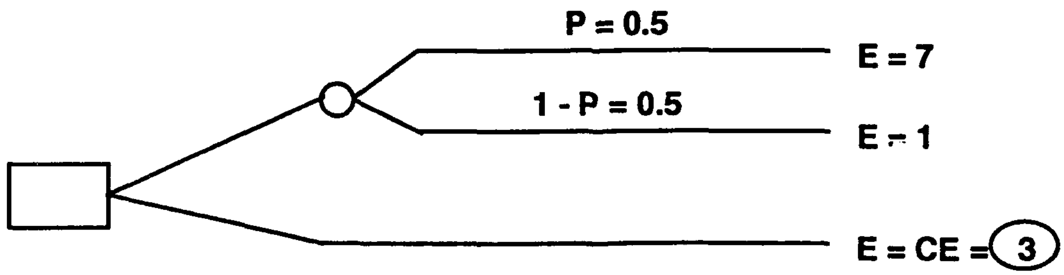
d. Now, consider the solvent has a cost of \$ 0.45, and health/safety impact and effectiveness values of 1 out of a 7 point scale (7 is better), but an environmental impact value of 7. What value of CE would you choose?



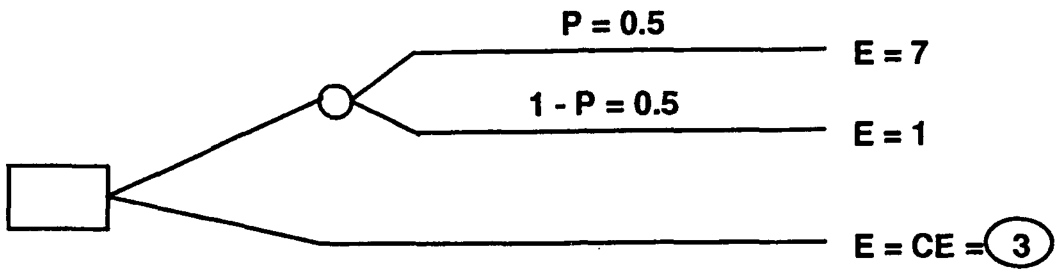
e. Now, consider the solvent has environmental impact, health/safety impact and effectiveness values of 1 out of a 7 point scale (7 is better). Both cost $ 21.37. What value for CE would you choose?



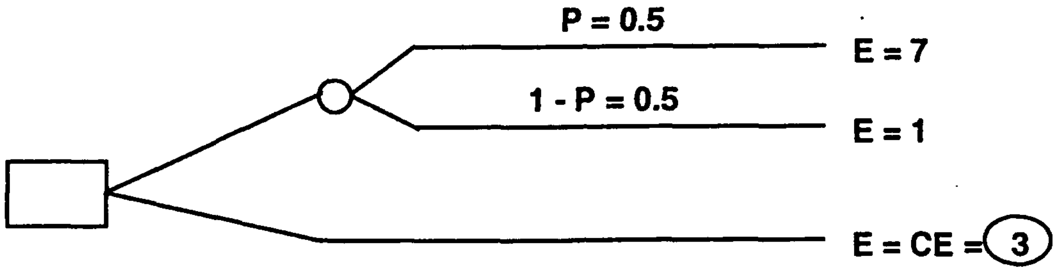
3. a. Now, consider the solvent has a cost of $ 0.45, and environmental impact, health/safety impact and process compatibility values of 1 out of a 7 point scale (7 is better). What value for CE would you choose?



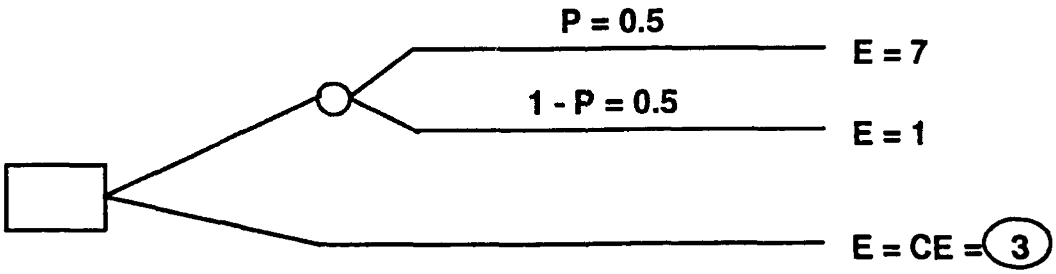
b. Now, consider the solvent has a cost of $ 0.45, and environmental impact, health/safety impact values of 1 out of a 7 point scale (7 is better), but process compatibility value of 7. What value for CE would you choose?



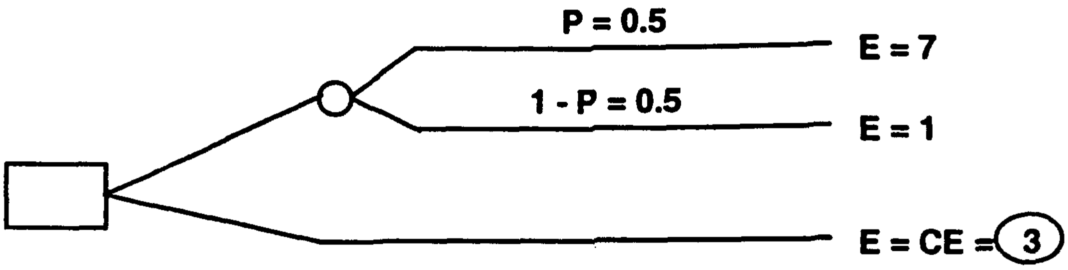
c. Now, consider the solvent has a cost of $ 0.45, and environmental impact, process compatibility values of 1 out of a 7 point scale (7 is better), but health/safety impact value of 7. What value of CE would you choose?



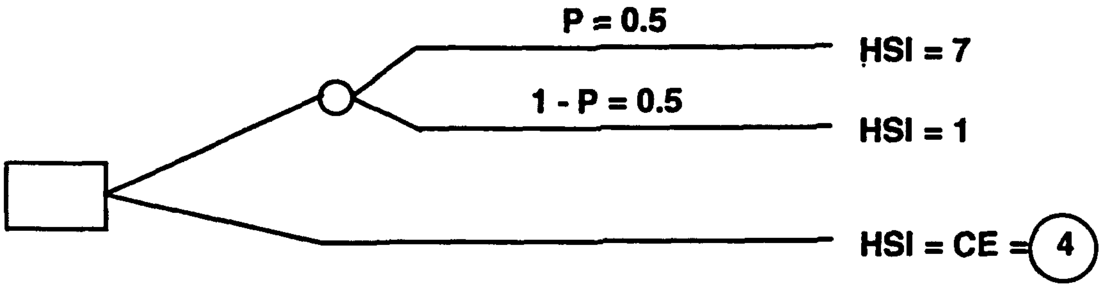
d. Now, consider the solvent has a cost of $ 0.45, and process compatibility, health/safety impact values of 1 out of a 7 point scale (7 is better), but an environmental impact value of 7. What value for CE would you choose?



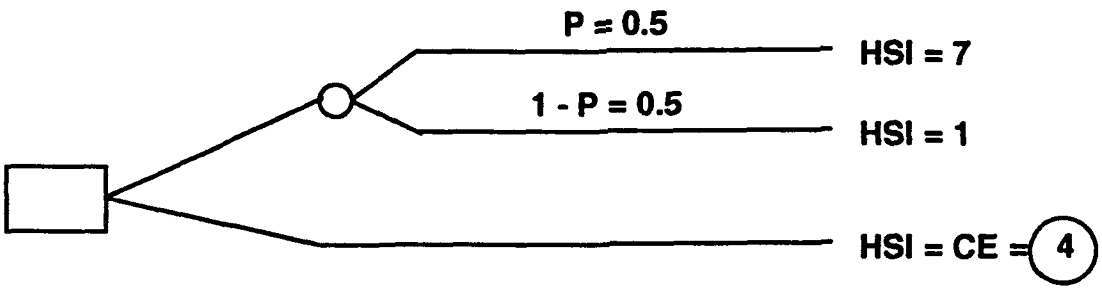
e. Now, consider the solvent has an environmental impact, health/safety impact, and process compatibility values of 1 out of a 7 point scale (7 is better), but cost $ 21.37. What value of CE would you choose?



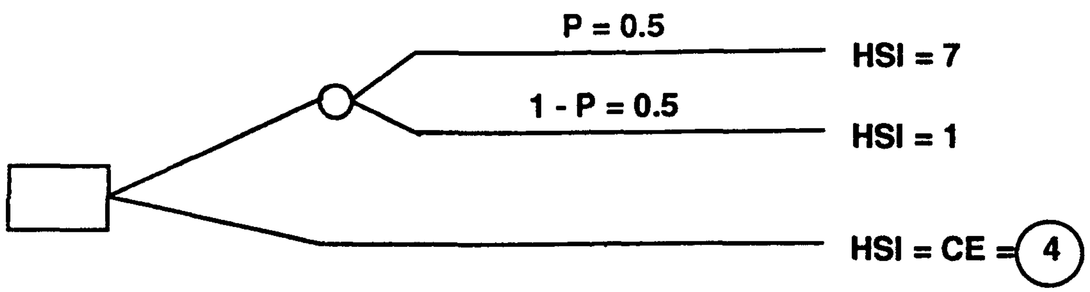
4. a. Now, consider the solvent has a cost of $ 0.45, and environmental impact, effectiveness and process compatibility values of 1 out of a 7 point scale (7 is better). What value of CE would you choose?



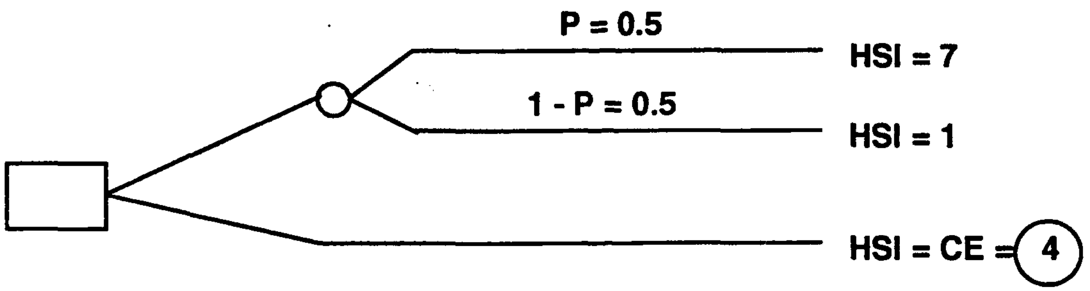
b. Now, consider solvent has a cost of $ 0.45, and environmental impact, and effectiveness values of 1 out of a 7 point scale (7 is better), but a process compatibility value of 7. What value for CE would you choose?



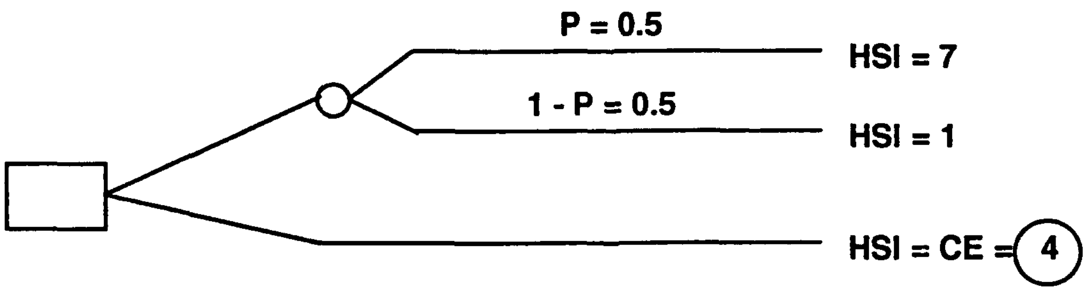
c. Now, consider the solvent has a cost of $ 0.45, and environmental impact, and process compatibility values of 1 out of a 7 point scale (7 is better), but an effectiveness value of 7. What value for CE would you choose?



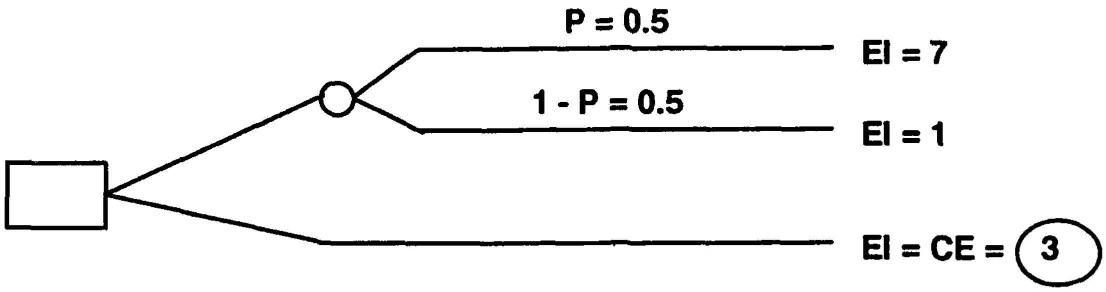
d. Now, consider the solvent has a cost of $ 0.45, effectiveness, and process compatibility values of 1 out of a 7 point scale (7 is better), but environmental impact value of 7. What value for CE would you choose?



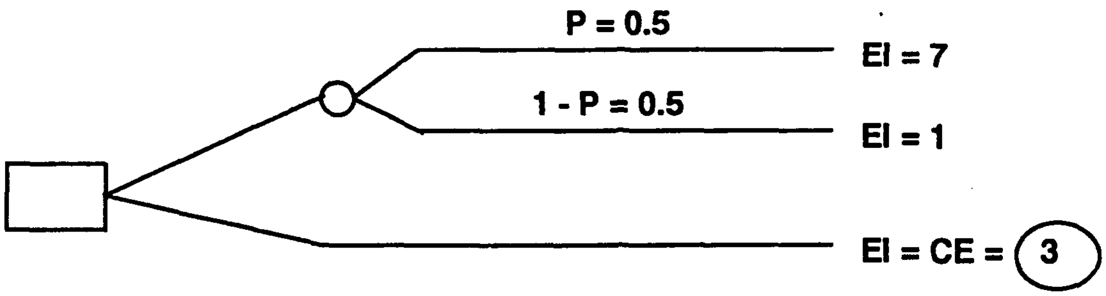
e. Now, consider the solvent has an environmental impact, effectiveness and process compatibility values of 1 out of a 7 point scale (7 is better), but cost $ 21.37. What value for CE would you choose?



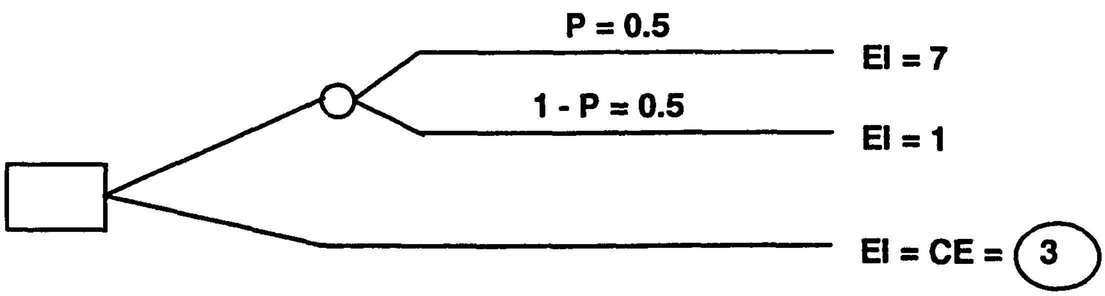
5. a. Now, consider the solvent has a cost of $ 0.45, health/safety impact, effectiveness and process compatibility values of 1 out of a 7 point scale (7 is better). What value for CE would you choose?



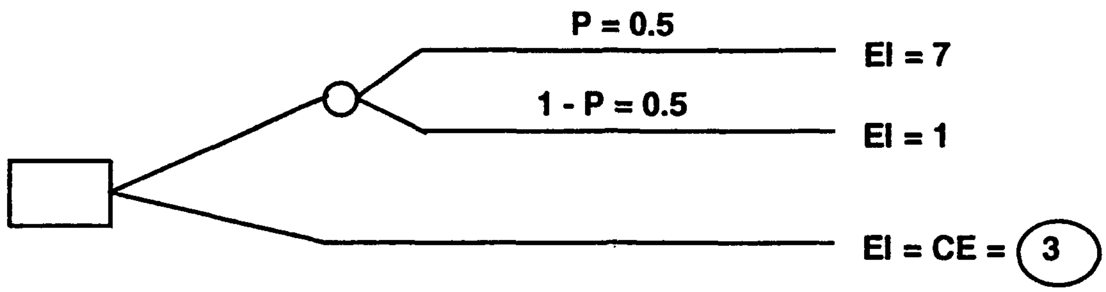
b. Now, consider the solvent has a cost of $ 0.45, health/safety impact, and effectiveness values of 1 out of a 7 point scale (7 is better), but process compatibility value of 7. What value for CE would you choose?



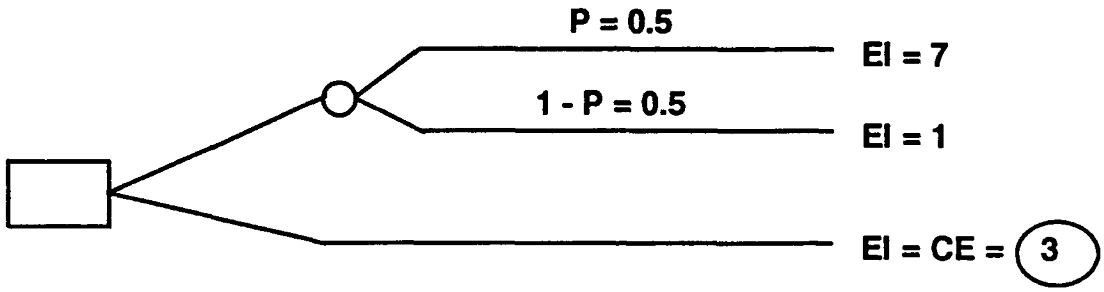
c. Now, consider the solvent has a cost of $ 0.45, health/safety impact, and process compatibility values of 1 out of a 7 point scale (7 is better), but an effectiveness value of 7. What value for CE would you choose?



d. Now, consider the solvent has a cost of $ 0.45, effectiveness, and process compatibility values of 1 out of a 7 point scale (7 is better), but a health/safety impact value of 7. What value for CE would you choose?



e. Now, consider the solvent has health/safety impact, effectiveness and process compatibility values of 1 out of a 7 point scale (7 is better), but cost $ 21.37. What value for CE would you choose?



This completes section two.

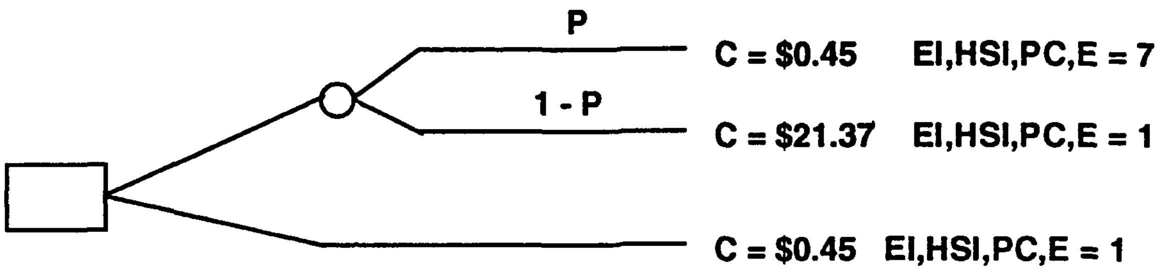
MAUT SURVEY

Section Three: Scaling Constants

Please answer the following decision questions.

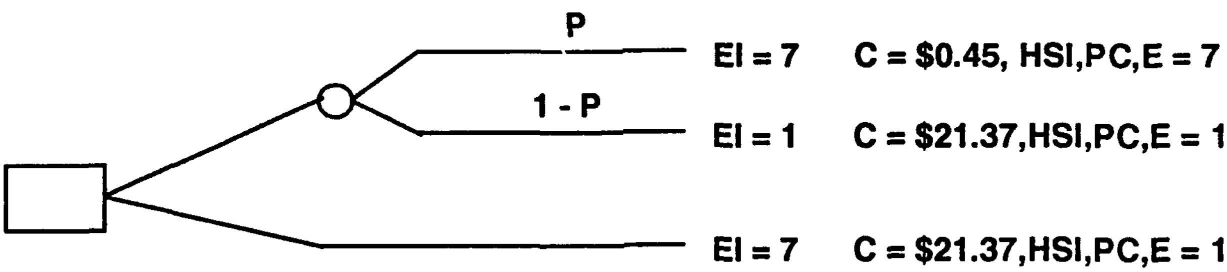
What probability (P) would make you indifferent between the lottery the sure thing? For simplicity, Environmental Impact is denoted EI, Process Compatibility is denoted PC, Effectiveness in denoted E, Health/Safety Impact is denoted HSI and Cost is denoted C.

1. Consider the decision below:



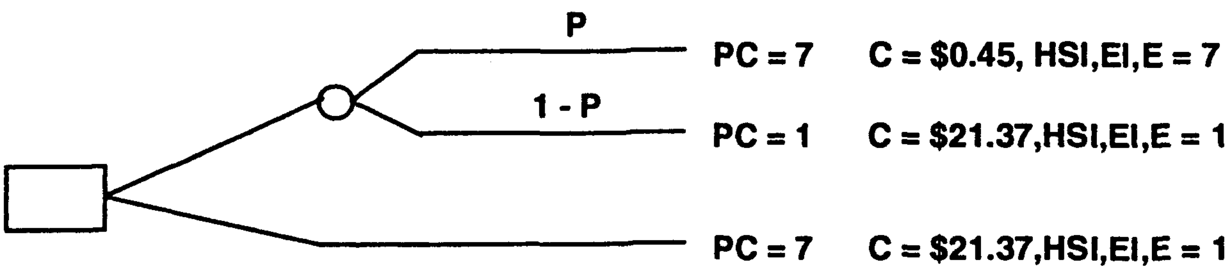
P = 0.15

2. Consider the decision below:



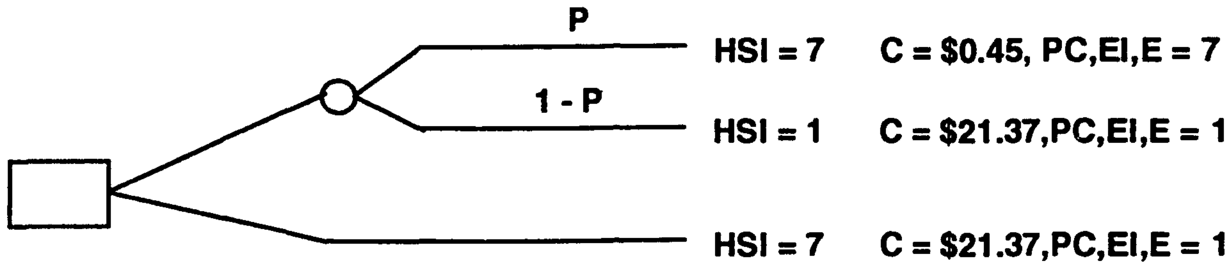
P = 0.60

3. Consider the decision below:



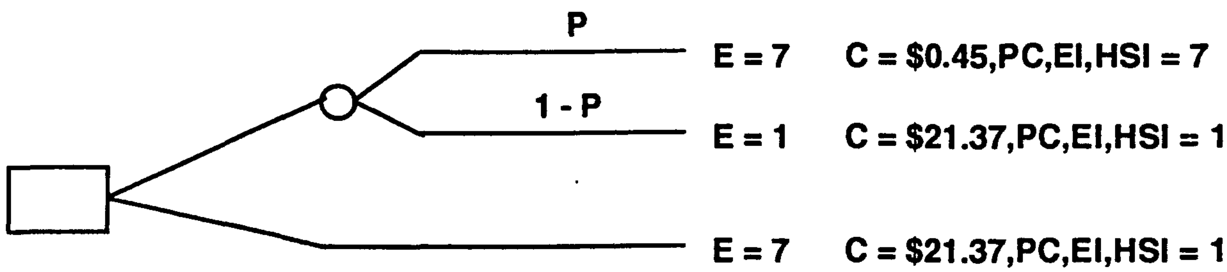
P = 0.40

4. Consider the decision below:



P = 0.80

5. Consider the decision below:



P = 0.70

This completes section 3.

MAUT SURVEY

Section four: Transforming Attributes/Criteria

Please answer the following lottery techniques.

1. Consider the criteria cost. What values for CE would make you indifferent to the decisions involving the lotteries and sure thing (CE) as shown below?

a. 50% chance cost = $ 0.45
50% chance cost = $ 21.37

what value for CE would you choose?
CE = 12

b. 50% chance cost = $ 0.45
50% chance cost = CE chosen in a

what new value for CE would you choose?
CE = 7

c. 50% chance cost = $21.37
50% chance cost = CE chosen in a

what value of CE would you choose?
CE = 17

2. Consider the criteria effectiveness. What values for CE would make you indifferent to the decisions involving the lotteries and sure thing (CE) as shown below?

a. 50% chance effectiveness = 2.73
50% chance effectiveness = 6.56

what value for CE would you choose?
CE = 4.0

b. 50% chance effectiveness = 2.73
50% chance effectiveness = CE chosen in a

what new value for CE would you choose?
CE = 3.3

c. 50% chance effectiveness = 6.56
50% chance effectiveness = CE chosen in a

what value for CE would you choose?
CE = 5.0

3. Consider the criteria process compatibility. What values for CE would make you indifferent to the decisions involving the lotteries and sure thing (CE) as shown below?

a. 50% chance process compatibility = 3.5
   50% chance process compatibility = 5.25

what value for CE would you choose?
CE = 3.8

b. 50% chance process compatibility = 3.5
   50% chance process compatibility = CE chosen in a

what new value for CE would you choose?
CE = 3.6

c. 50% chance process compatibility = 5.25
   50% chance process compatibility = CE chosen in a

what value for CE would you choose?
CE = 4.1

4. Consider the criteria health/safety impact. What values for CE would make you indifferent to the decisions involving the lotteries and sure thing (CE) as shown below?

a. 50% chance health/safety impact = 1.75
   50% chance health/safety impact = 5.51

what value for CE would you choose?
CE = 2.3

b. 50% chance health/safety impact = 1.75
   50% chance health/safety impact = CE chosen in a

what new value for CE would you choose?
CE = 1.9

c. 50% chance health/safety impact = 5.51
   50% chance health/safety impact = CE chosen in a

what value for CE would you choose?
CE = 2.8

5. Consider the criteria environmental impact. What values for CE would make you indifferent to the decisions involving the lotteries and sure thing (CE) as shown below?

a. 50% chance environmental impact = 1.8
   50% chance environmental impact = 5.0

what value for CE would you choose?
CE = 2.5

b. 50% chance environmental impact = 1.8
   50% chance environmental impact = CE chosen in a

what new value for CE would you choose?
CE = 2.1

c. 50% chance environmental impact = 5
   50% chance environmental impact = CE chosen in a

what value for CE would you choose?
CE = 3.0

This completes section four.

Appendix D: Survey Results From the Expert Team

The expert team was provided a survey which requested them to do two things. The first was to evaluate alternative data and rank the alternative criteria values on a 7 point scale (7 being best). The complete results are provided in Chapter 4. The resulting ratings using the geometric average of inputs are provided below in Table D-1.

	Solvent Alternatives				
CRITERIA	Ardrox	Desoclean	Dynasolve	Metalube	PF 145 HP
Env. Impact	5.01	1.84	2.83	4.49	3.12
Health Impact	5.51	1.75	3.14	4.49	2.64
Effectiveness	3.80	6.55	5.24	2.84	2.73
Process Com.	3.90	4.17	5.25	4.04	3.49

Table D-1: Expert Team Results (Geometrically Averaged Values)

For task two, the experts were asked to consider the following list of factors and their reference numbers.

Criteria Factors

1. biodegradibility
2. toxicity
3. vapor pressure
4. evaporation rate
5. non volatile residue
6. volatile organic carbon content
7. odor
8. hazardous constituents
9. cleaning time required
10. cleaning effectiveness
11. startup time requirements
12. permitting requirements
13. 17 industrial toxin lists
14. PEL/TLV
15. safety equipment requirements
16. explosiveness
17. ignitability
18. reactivity
19. disposal costs
20. purchase costs
21. scrubbing effort required
22. ozone depleting substance characteristics
23. training requirements
24. startup equipment purchase requirements

Given the list, the experts were asked to indentify which factors they thought impacted the specific criteria. The list of inputs is provided in Table D-2.

Expert	Env. Impact	Health Impact	Effectiveness	Proc. Comp.
1	1, 2, 4, 6, 8, 13	3, 7, 14, 16, 17, 18	5, 10, 11, 21	4, 7, 9, 12, 15, 19, 20, 23, 24, mil spec
2	1, 2, 3, 6, 8, 13, 16, 17, 18, 19, 20	2, 3, 4, 6, 7, 8, 10, 13, 15, 16	5, 9, 10, 21, 23	4, 5, 7, 8, 9, 10, 11, 12, 15, 17, 18, 19, 20, 21, 23, 24
3	1, 2, 22	2, 16, 17	9, 10, 21	9, 15, 20, 23, 24
4	1, 6, 12, 13, 22,tri, rcra reporting	2, 8, 15, 16, 17, 18, 23	4, 10, 21, 23	5, 7, 9, 11, 15, 18, 19, 20, 23, 24
5	1, 8, 12, 13, 22	2, 7, 14, 15, 16, 17	5, 9, 10	3, 4, 5, 11, 16, 17, 18, 19, 20, 21
6	1, 2, 3, 4, 6, 13, 17, 18, 19, 21, 22	2, 3, 7, 8, 9, 13, 14, 16, 17, 21	5, 9, 10, 11, 12, 19, 20	5, 6, 9, 10, 15, 16, 17, 18, 19, 22, 23
7	1, 3, 4, 8, 13, 22	1, 2, 7, 8, 13, 15, 17, 18	9, 10, 18, 19, 20, 21, 23, 24	5, 8, 17, 18, 21
Significant Factors (reffered >= 4)	1, 2, 6, 8, 13, 22	2, 7, 8, 15, 16, 17	5, 9, 10, 21	5, 7, 9, 15, 17, 18, 19, 20, 23, 24

Table D-1: Expert Criteria Factors List

APPENDIX E

EXPERTCHOICE COMPUTER ANALYSIS

:\AHP

choose best solvent alternative

GOAL	
L	1.000
G	1.000

	COST	EFF.	PROC COM	E IMPACT	H IMPACT
L	0.044	0.231	0.105	0.142	0.478
G	0.044	0.231	0.105	0.142	0.478
DYNASOLV					
L	0.036	0.255	0.264	0.187	0.186
G	0.002	0.059	0.028	0.026	0.089
MC509-4U					
L	0.369	0.144	0.197	0.217	0.265
G	0.016	0.033	0.021	0.031	0.127
DESO 45					
L	0.047	0.288	0.197	0.098	0.089
G	0.002	0.066	0.021	0.014	0.043
ARDROX					
L	0.486	0.169	0.171	0.311	0.301
G	0.021	0.039	0.018	0.044	0.144
PF 145					
L	0.062	0.144	0.171	0.187	0.159
G	0.003	0.033	0.018	0.026	0.076

ARDROX --- ARDROX 180 BH
COST --- COST OF SOLVENT
DESO 45 --- DESOCLEAN 45
DYNASOLV --- DYNASOLVE
E IMPACT --- ENVIRONMENTAL IMPACT
EFF. --- EFFECTIVENESS OF SOLVENT
H IMPACT --- HEALTH/SAFETY IMPACT
MC509-4U --- METALUBE 509 4U
PF 145 --- PF 145 HP
PROC COM --- PROCESS COMPATIBILITY OF SOLVENT

L --- LOCAL PRIORITY: PRIORITY RELATIVE TO PARENT
G --- GLOBAL PRIORITY: PRIORITY RELATIVE TO GOAL

JUDGMENTS WITH RESPECT TO
GOAL

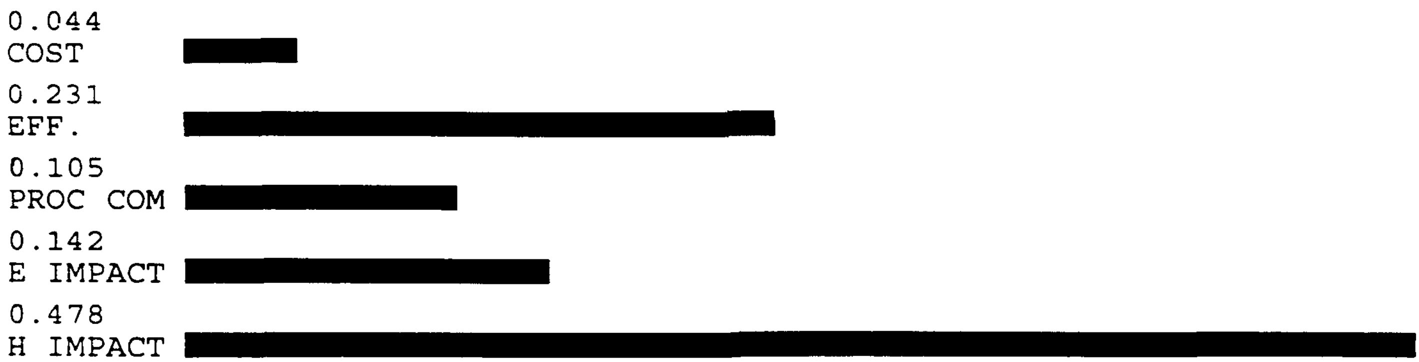
	COST	EFF.	PROC COM	E IMPACT	H IMPACT
COST		(5.0)	(4.0)	(2.5)	(8.0)
EFF.			2.0	3.0	(3.5)
PROC COM				(2.5)	(4.5)
E IMPACT					(3.0)
H IMPACT					

Matrix entry indicates that ROW element is ___
1 EQUALLY 3 MODERATELY 5 STRONGLY 7 VERY STRONGLY 9 EXTREMELY
more IMPORTANT than COLUMN element unless enclosed in parenthesis.

GOAL: choose best solvent alternative

COST --- COST OF SOLVENT
E IMPACT --- ENVIRONMENTAL IMPACT
EFF. --- EFFECTIVENESS OF SOLVENT
H IMPACT --- HEALTH/SAFETY IMPACT
PROC COM --- PROCESS COMPATIBILITY OF SOLVENT

PRIORITIES



INCONSISTENCY RATIO = 0.068.

JUDGMENTS WITH RESPECT TO
COST < GOAL

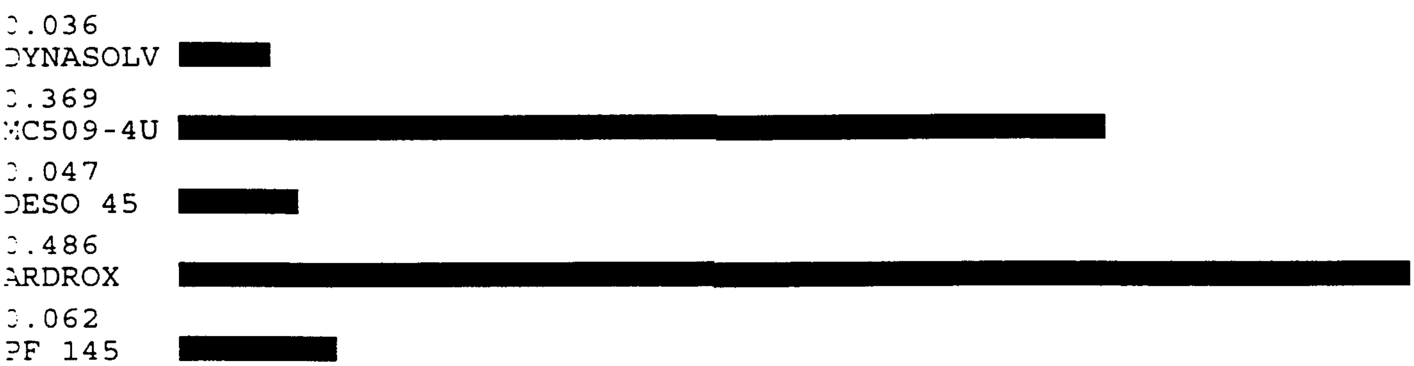
	DYNASOLV	MC509-4U	DESO 45	ARDROX	PF 145
DYNASOLV		(9.0)	(2.0)	(9.0)	(2.0)
MC509-4U			9.0	(2.0)	9.0
DESO 45				(9.0)	(2.0)
ARDROX					9.0
PF 145					

Matrix entry indicates that ROW element is ___
1 EQUALLY 3 MODERATELY 5 STRONGLY 7 VERY STRONGLY 9 EXTREMELY
more PREFERABLE than COLUMN element unless enclosed in parenthesis.

GOAL: choose best solvent alternative

ARDROX --- ARDROX 180 BH
COST --- COST OF SOLVENT
DESO 45 --- DESOCLEAN 45
DYNASOLV --- DYNASOLVE
MC509-4U --- METALUBE 509 4U
PF 145 --- PF 145 HP

PRIORITIES



INCONSISTENCY RATIO = 0.044.

JUDGMENTS WITH RESPECT TO
EFF. < GOAL

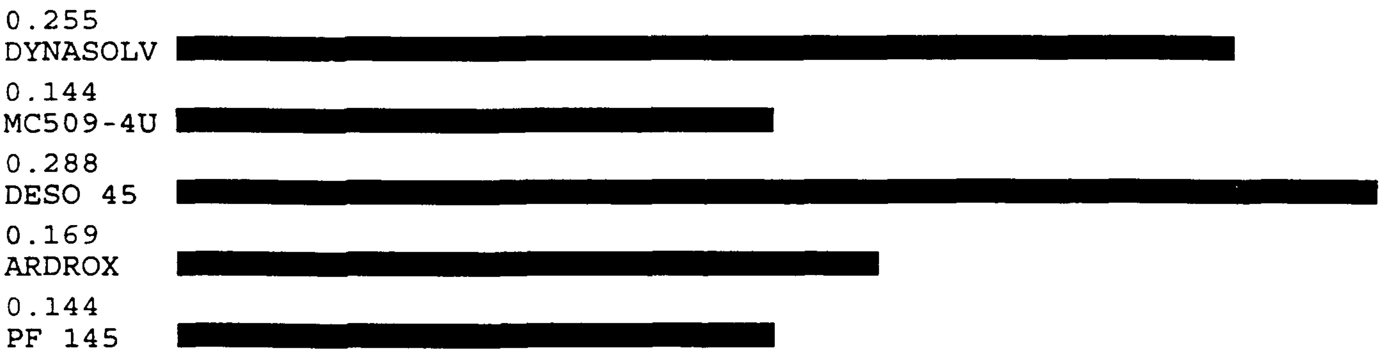
	DYNASOLV	MC509-4U	DESO 45	ARDROX	PF 145
DYNASOLV		2.0	1.0	1.0	2.0
MC509-4U			(2.0)	1.0	1.0
DESO 45				2.0	2.0
ARDROX					1.0
PF 145					

Matrix entry indicates that ROW element is ___
1 EQUALLY 3 MODERATELY 5 STRONGLY 7 VERY STRONGLY 9 EXTREMELY
more PREFERABLE than COLUMN element unless enclosed in parenthesis.

GOAL: choose best solvent alternative

ARDROX --- ARDROX 180 BH
DESO 45 --- DESOCLEAN 45
DYNASOLV --- DYNASOLVE
EFF. --- EFFECTIVENESS OF SOLVENT
MC509-4U --- METALUBE 509 4U
PF 145 --- PF 145 HP

PRIORITIES



INCONSISTENCY RATIO = 0.013.

JUDGMENTS WITH RESPECT TO
PROC COM < GOAL

	DYNASOLV	MC509-4U	DESO 45	ARDROX	PF 145
DYNASOLV		1.0	1.0	2.0	2.0
MC509-4U			1.0	1.0	1.0
DESO 45				1.0	1.0
ARDROX					1.0
PF 145					

Matrix entry indicates that ROW element is ___
1 EQUALLY 3 MODERATELY 5 STRONGLY 7 VERY STRONGLY 9 EXTREMELY
more PREFERABLE than COLUMN element unless enclosed in parenthesis.

GOAL: choose best solvent alternative

ARDROX --- ARDROX 180 BH
DESO 45 --- DESOCLEAN 45
DYNASOLV --- DYNASOLVE
MC509-4U --- METALUBE 509 4U
PF 145 --- PF 145 HP
PROC COM --- PROCESS COMPATIBILITY OF SOLVENT

PRIORITIES

INCONSISTENCY RATIO = 0.017.

JUDGMENTS WITH RESPECT TO
E IMPACT < GOAL

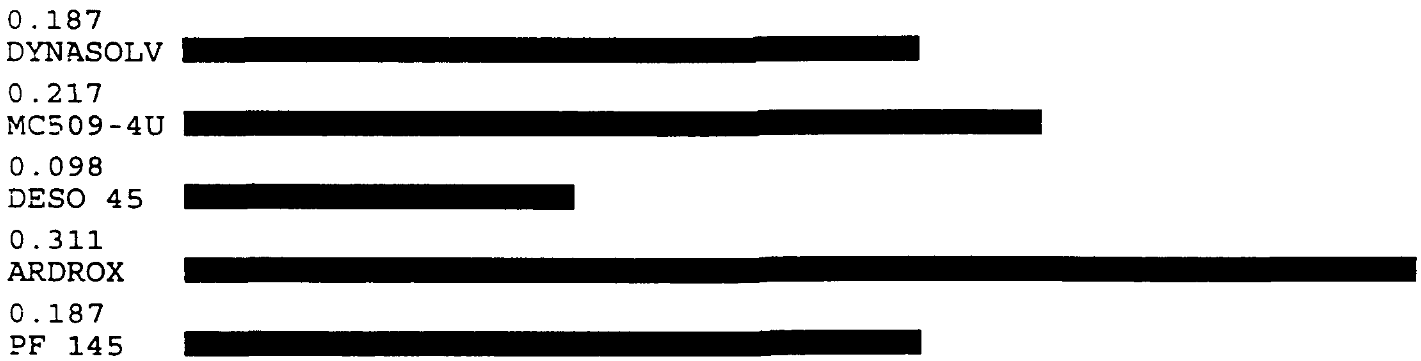
	DYNASOLV	MC509-4U	DESO 45	ARDROX	PF 145
DYNASOLV		1.0	2.0	(2.0)	1.0
MC509-4U			2.0	1.0	1.0
DESO 45				(3.0)	(2.0)
ARDROX					2.0
PF 145					

Matrix entry indicates that ROW element is ___
1 EQUALLY 3 MODERATELY 5 STRONGLY 7 VERY STRONGLY 9 EXTREMELY
more PREFERABLE than COLUMN element unless enclosed in parenthesis.

GOAL: choose best solvent alternative

ARDROX --- ARDROX 180 BH
DESO 45 --- DESOCLEAN 45
DYNASOLV --- DYNASOLVE
E IMPACT --- ENVIRONMENTAL IMPACT
MC509-4U --- METALUBE 509 4U
PF 145 --- PF 145 HP

PRIORITIES



INCONSISTENCY RATIO = 0.012.

JUDGMENTS WITH RESPECT TO
H IMPACT < GOAL

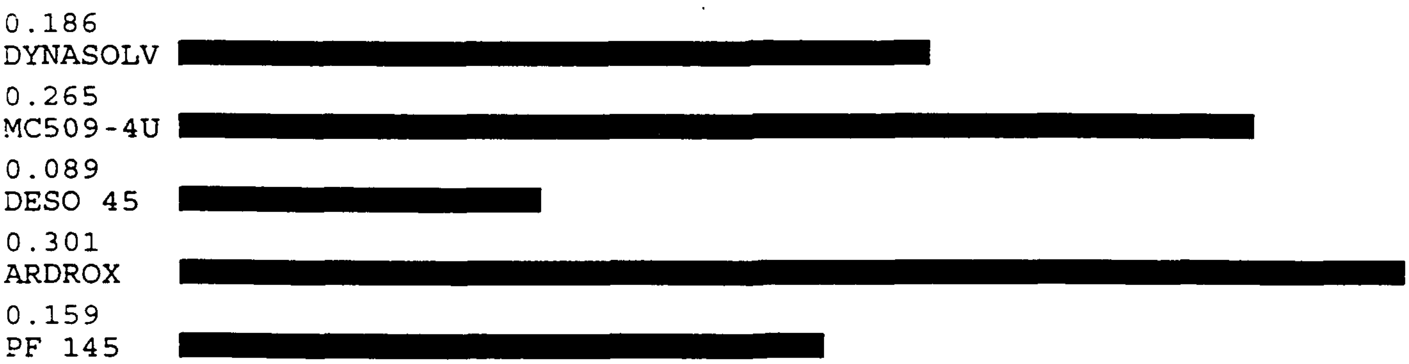
	DYNASOLV	MC509-4U	DESO 45	ARDROX	PF 145
DYNASOLV		1.0	2.0	(2.0)	1.0
MC509-4U			3.0	1.0	2.0
DESO 45				(3.0)	(2.0)
ARDROX					2.0
PF 145					

Matrix entry indicates that ROW element is ___
1 EQUALLY 3 MODERATELY 5 STRONGLY 7 VERY STRONGLY 9 EXTREMELY
more PREFERABLE than COLUMN element unless enclosed in parenthesis.

GOAL: choose best solvent alternative

ARDROX --- ARDROX 180 BH
DESO 45 --- DESOCLEAN 45
DYNASOLV --- DYNASOLVE
H IMPACT --- HEALTH/SAFETY IMPACT
MC509-4U --- METALUBE 509 4U
PF 145 --- PF 145 HP

PRIORITIES



INCONSISTENCY RATIO = 0.013.

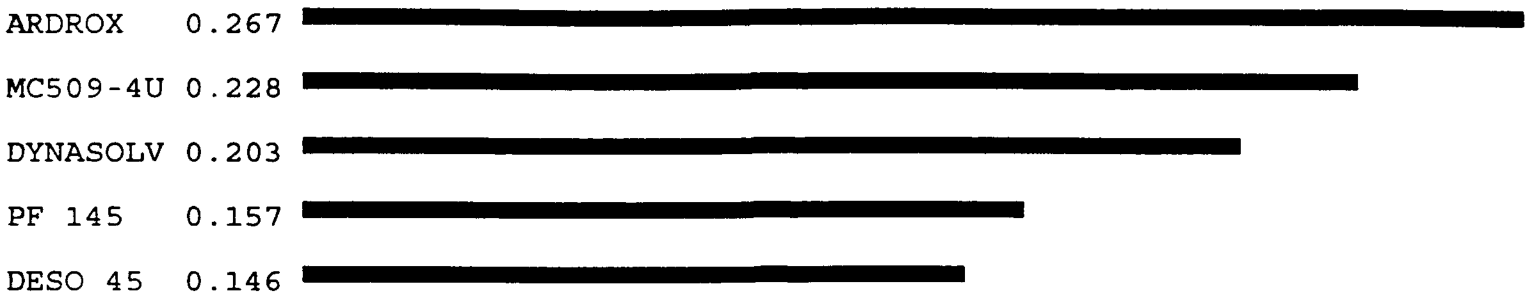
choose best solvent alternative
Sorted Details for Synthesis of Leaf Nodes with respect to GOAL
DISTRIBUTIVE MODE

LEVEL 1	LEVEL 2	LEVEL 3	LEVEL 4	LEVEL 5
H IMPACT =0.478				
.	ARDROX =0.144			
.	MC509-4U =0.127			
.	DYNASOLV =0.089			
.	PF 145 =0.076			
.	DESO 45 =0.043			
EFF. =0.231				
.	DESO 45 =0.066			
.	DYNASOLV =0.059			
.	ARDROX =0.039			
.	MC509-4U =0.033			
.	PF 145 =0.033			
E IMPACT =0.142				
.	ARDROX =0.044			
.	MC509-4U =0.031			
.	DYNASOLV =0.026			
.	PF 145 =0.026			
.	DESO 45 =0.014			
PROC COM =0.105				
.	DYNASOLV =0.028			
.	MC509-4U =0.021			
.	DESO 45 =0.021			
.	ARDROX =0.018			
.	PF 145 =0.018			
COST =0.044				
.	ARDROX =0.021			
.	MC509-4U =0.016			
.	PF 145 =0.003			
.	DESO 45 =0.002			
.	DYNASOLV =0.002			

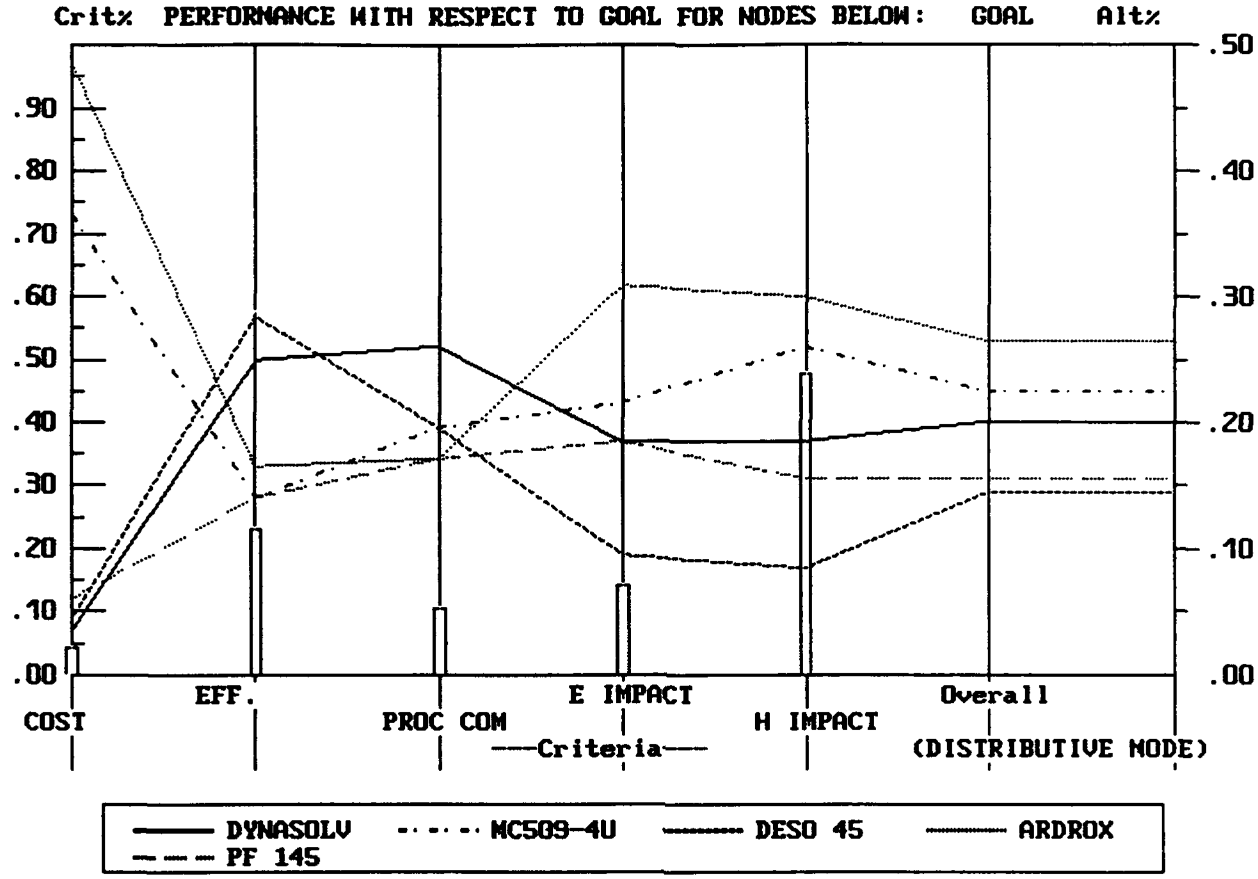
choose best solvent alternative

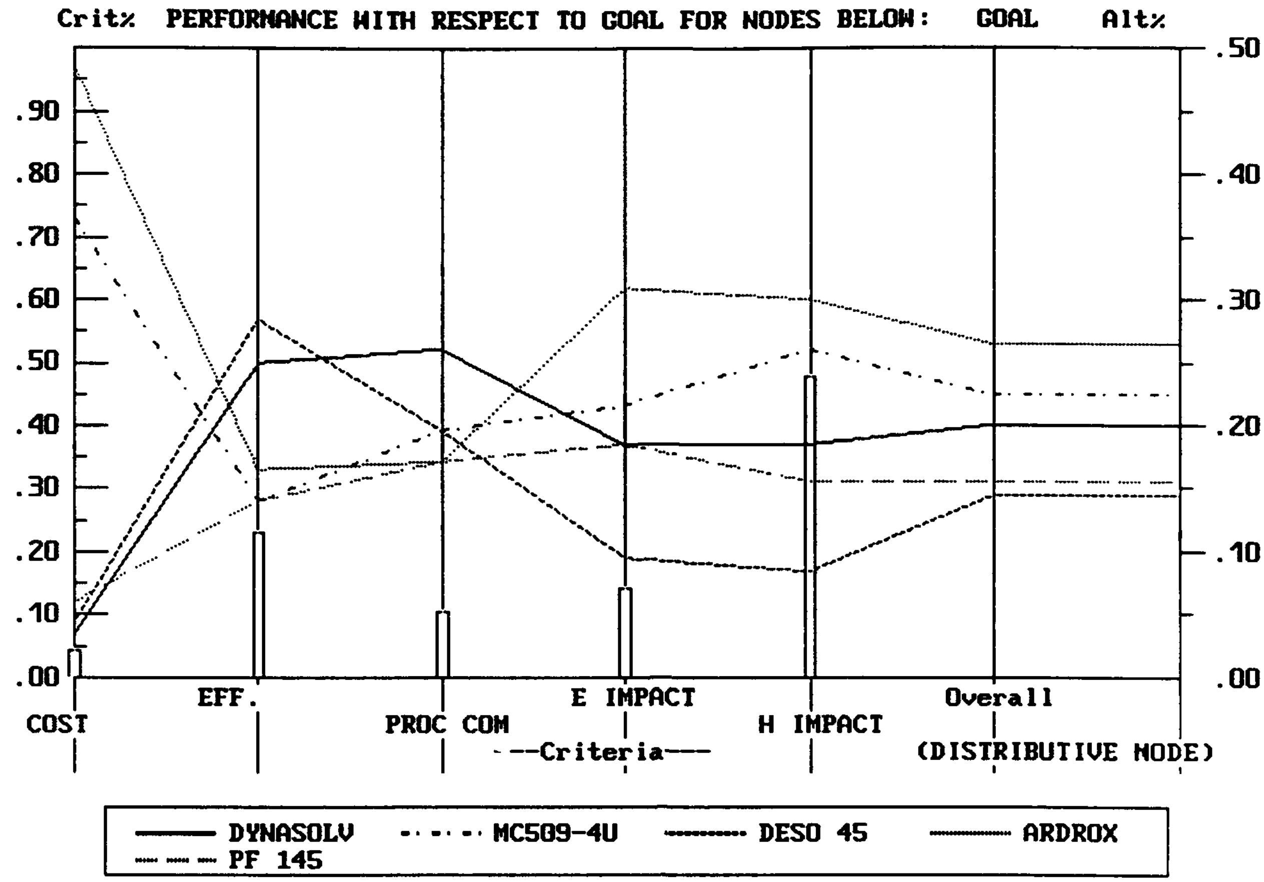
Synthesis of Leaf Nodes with respect to GOAL
DISTRIBUTIVE MODE

OVERALL INCONSISTENCY INDEX = 0.04



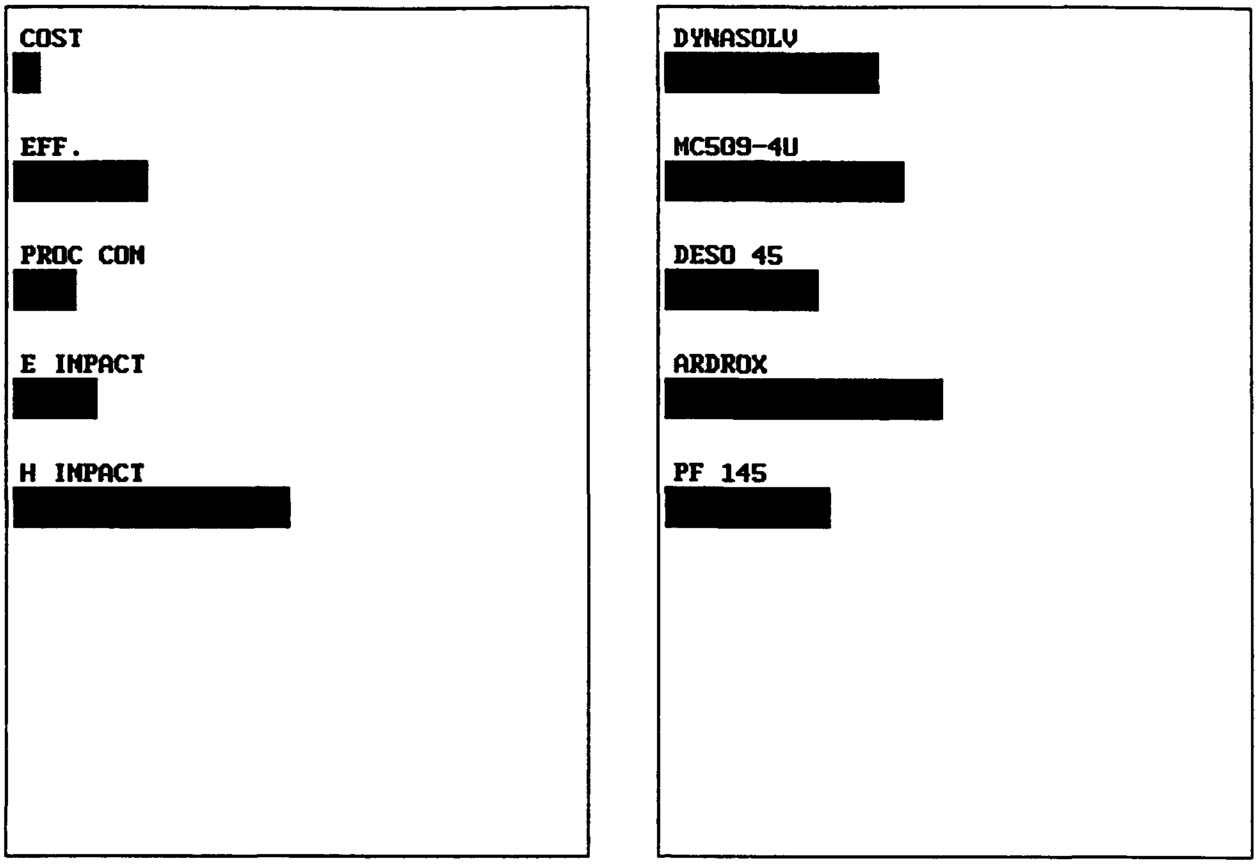
ARDROX --- ARDROX 180 BH
DESO 45 --- DESOCLEAN 45
DYNASOLV --- DYNASOLVE
MC509-4U --- METALUBE 509 4U
PF 145 --- PF 145 HP

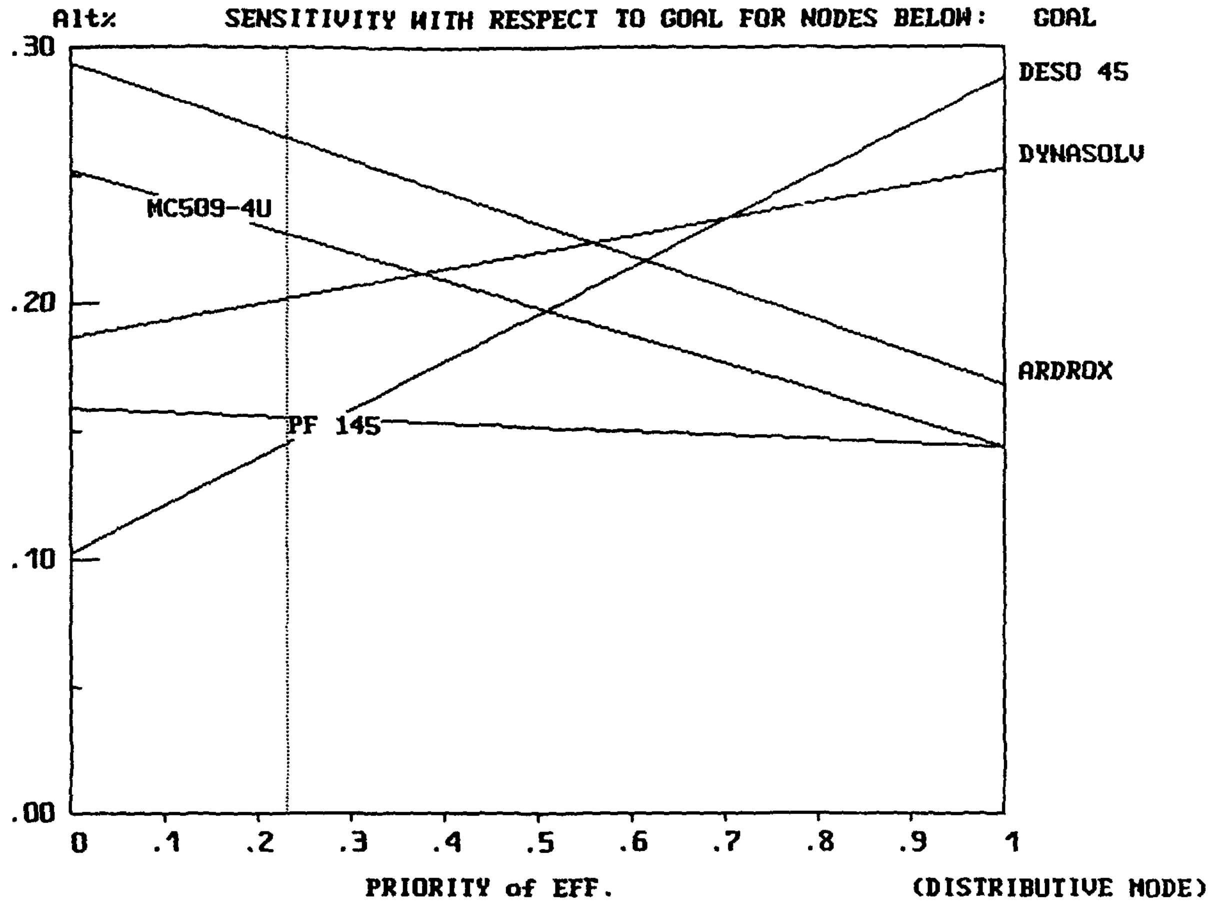

Crit% PERFORMANCE WITH RESPECT TO GOAL FOR NODES BELOW: GOAL Alt%
.90
.80
.70
.60
.50
.40
.30
.20
.10
.00
.50
.40
.30
.20
.10
.00
COST
EFF.
PROC COM
E IMPACT
H IMPACT
Overall
---Criteria---
(DISTRIBUTIVE NODE)
DYNASOLV
MC509-4U
DESO 45
ARDROX
PF 145

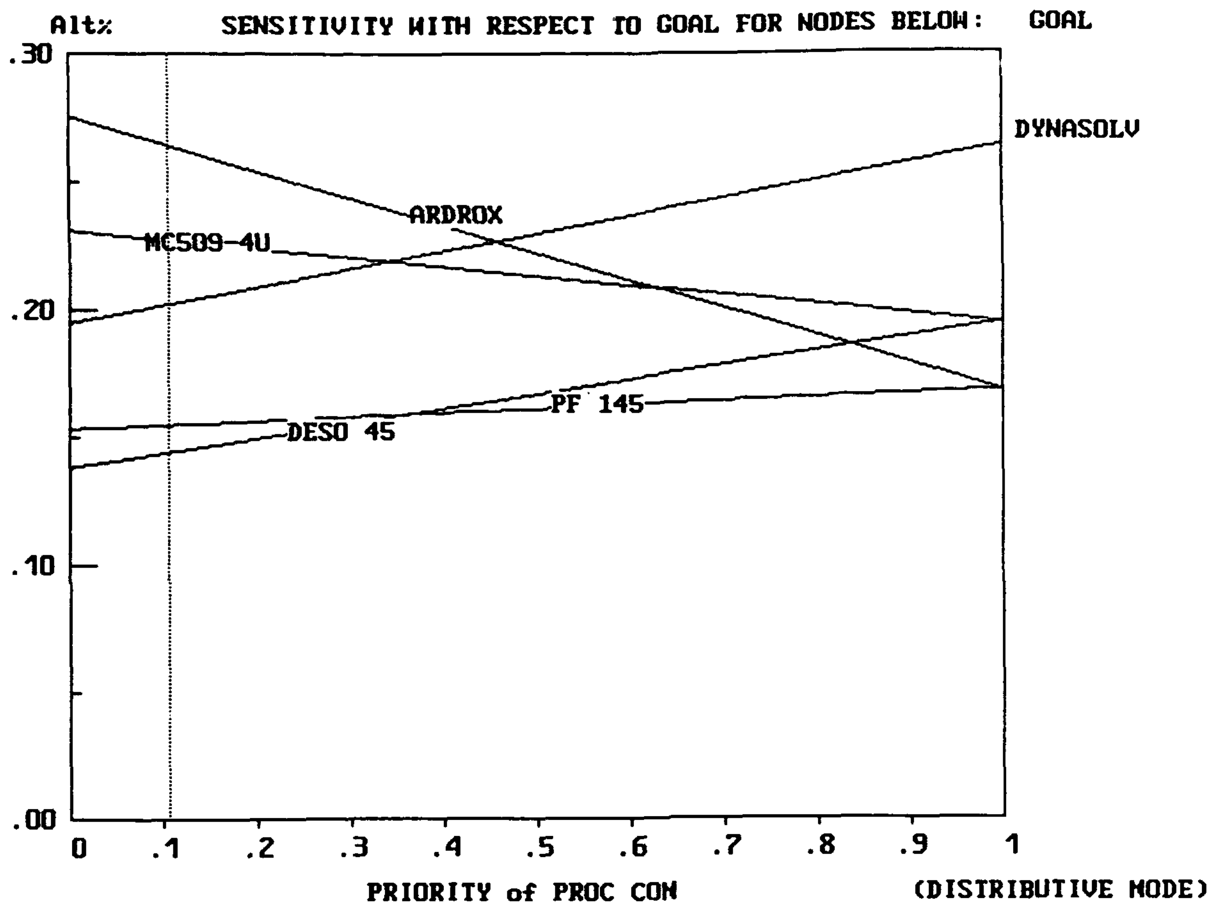


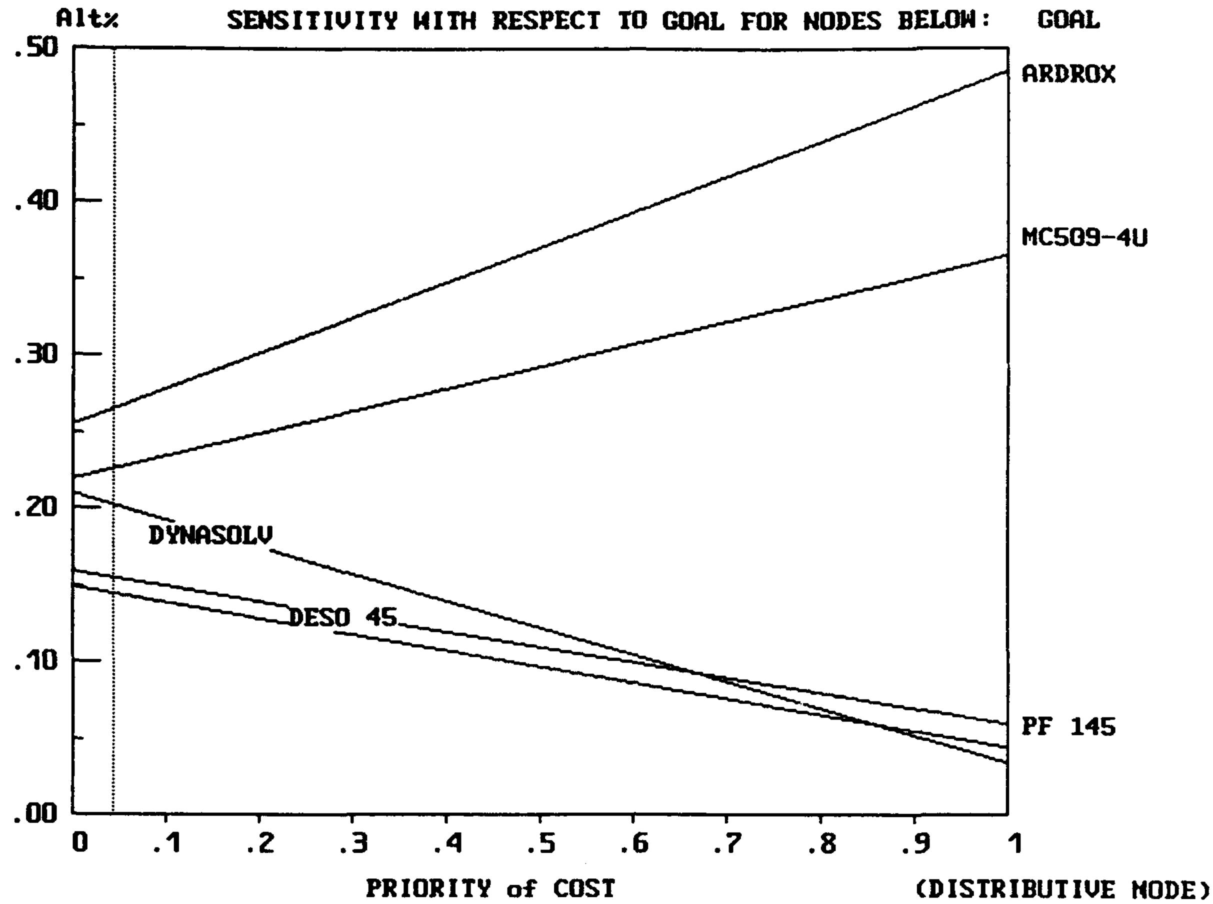
Crit% PERFORMANCE WITH RESPECT TO GOAL FOR NODES BELOW: GOAL Alt%
.90
.80
.70
.60
.50
.40
.30
.20
.10
.00
.50
.40
.30
.20
.10
.00
COST
EFF.
PROC COM
E IMPACT
H IMPACT
Overall
(DISTRIBUTIVE NODE)
---Criteria---
DYNASOLV
MC509-4U
DESO 45
ARDROX
PF 145

CRITERIA (DISTRIBUTIVE MODE) ALTERNATIVES




Alt%
SENSITIVITY WITH RESPECT TO GOAL FOR NODES BELOW: GOAL
.30
.20
.10
.00
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1
DESO 45
DYNASOLV
MC509-4U
ARDROX
PF 145
PRIORITY of EFF.
(DISTRIBUTIVE NODE)


Alt%
SENSITIVITY WITH RESPECT TO GOAL FOR NODES BELOW: GOAL
.30
.20
.10
.00
DYNASOLV
ARDROX
MC509-4U
PF 145
DESO 45
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1
PRIORITY of PROC CON
(DISTRIBUTIVE MODE)


Alt%
SENSITIVITY WITH RESPECT TO GOAL FOR NODES BELOW: GOAL
.50
.40
.30
.20
.10
.00
ARDROX
MC509-4U
DYNASOLV
DESO 45
PF 145
0
.1
.2
.3
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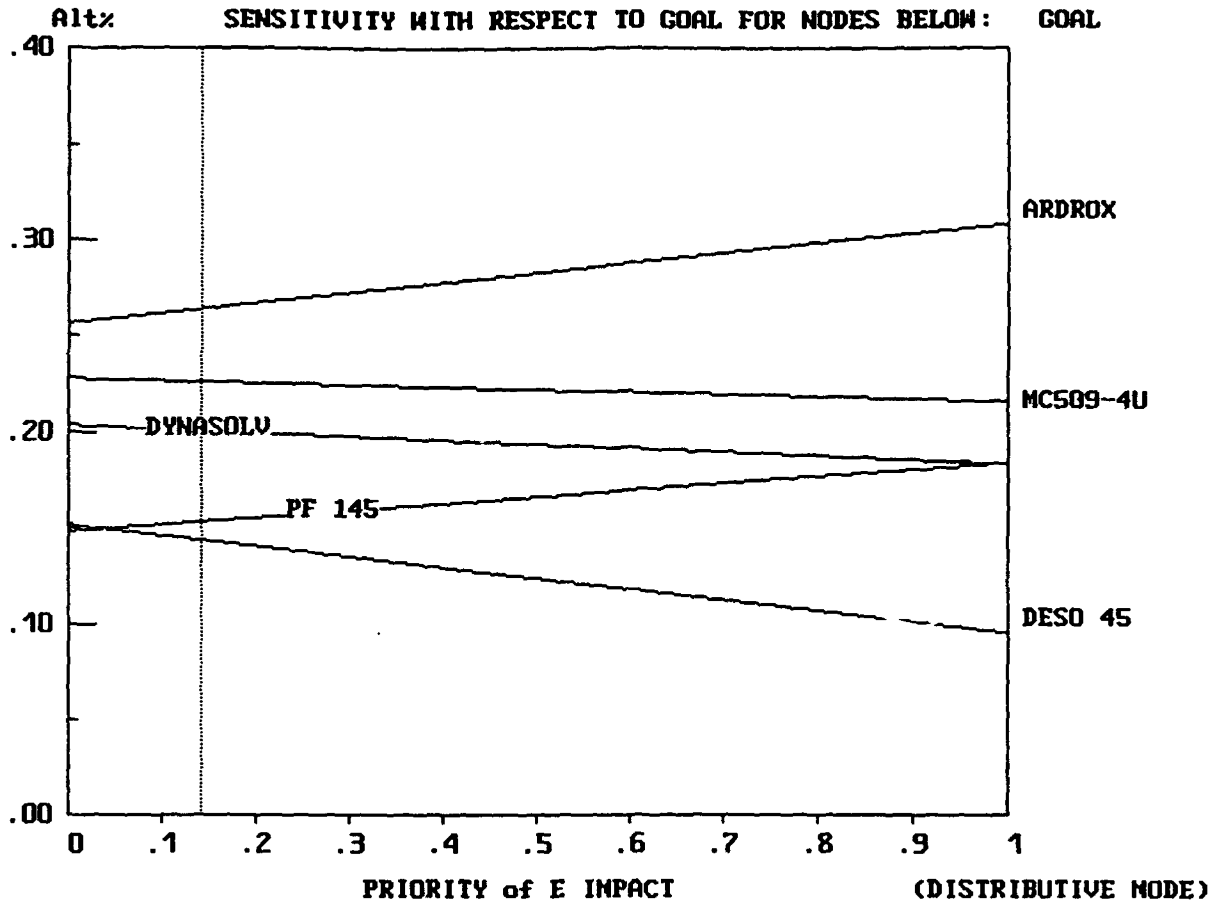
.8
.9
1
PRIORITY of COST
(DISTRIBUTIVE NODE)


Alt%
SENSITIVITY WITH RESPECT TO GOAL FOR NODES BELOW: GOAL
.40
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ARDROX
MC509-4U
DYNASOLV
PF 145
DESO 45
0
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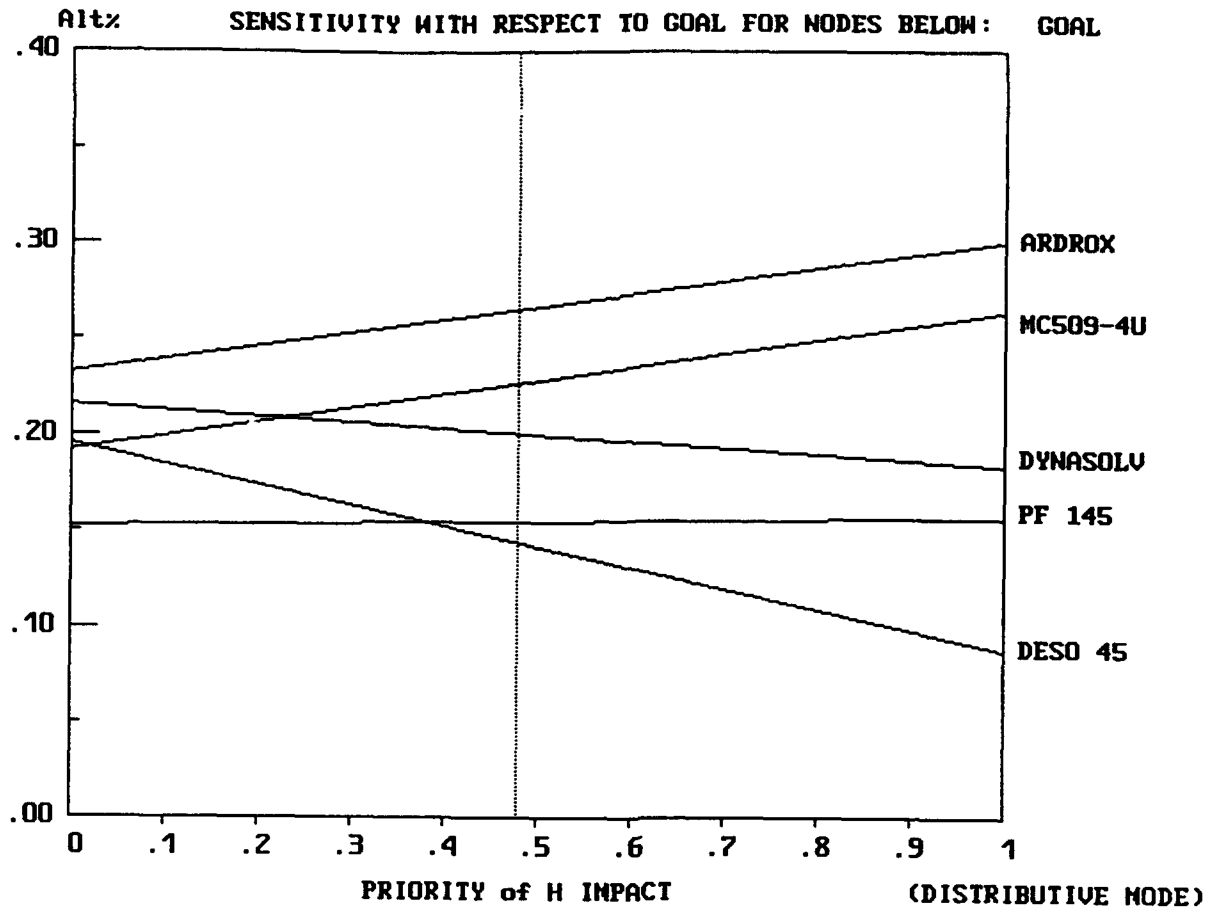
1
PRIORITY of E IMPACT
(DISTRIBUTIVE NODE)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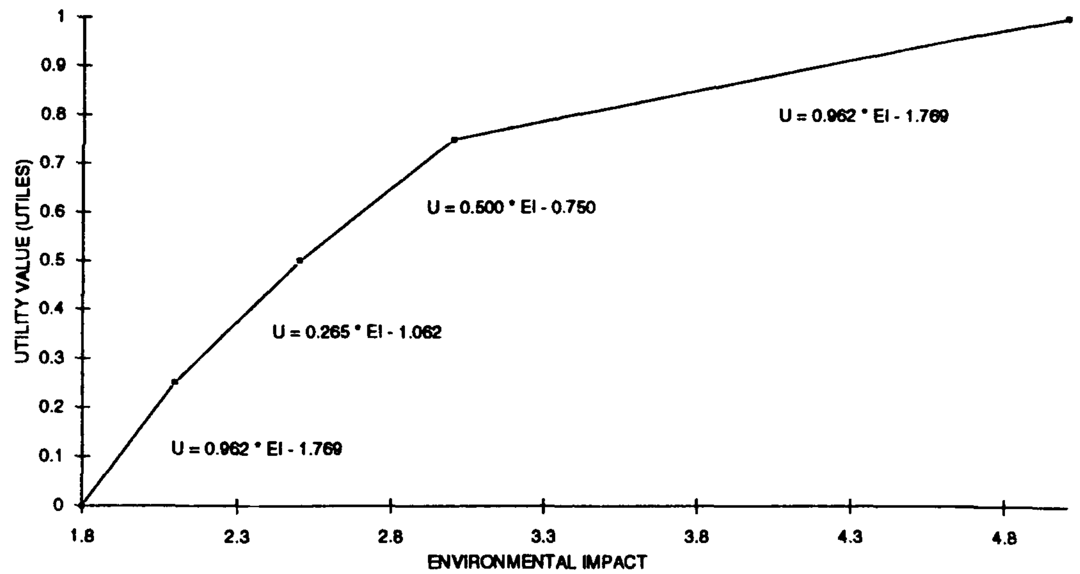
PRIORITY of H IMPACT
(DISTRIBUTIVE MODE)

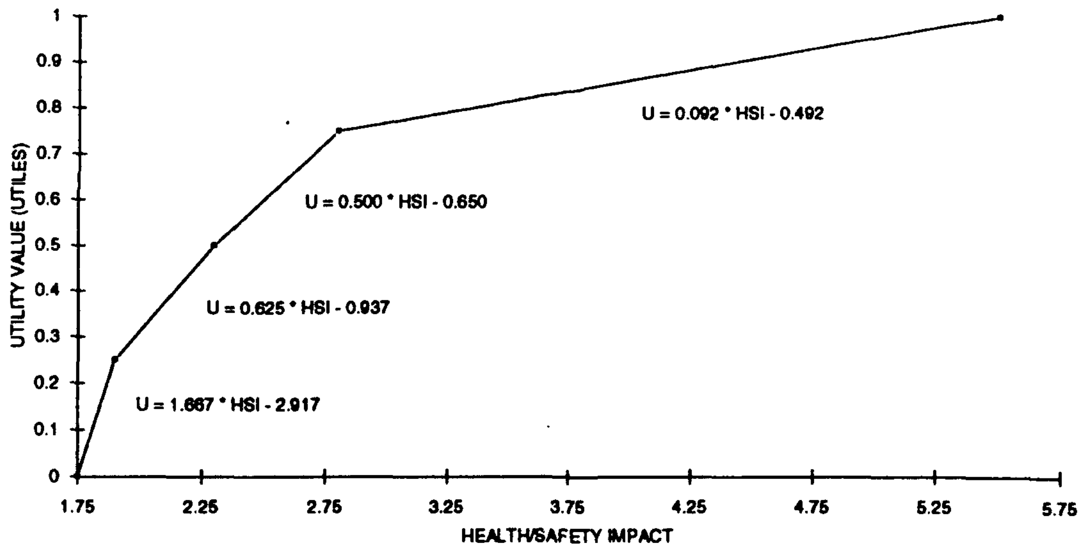
APPENDIX F

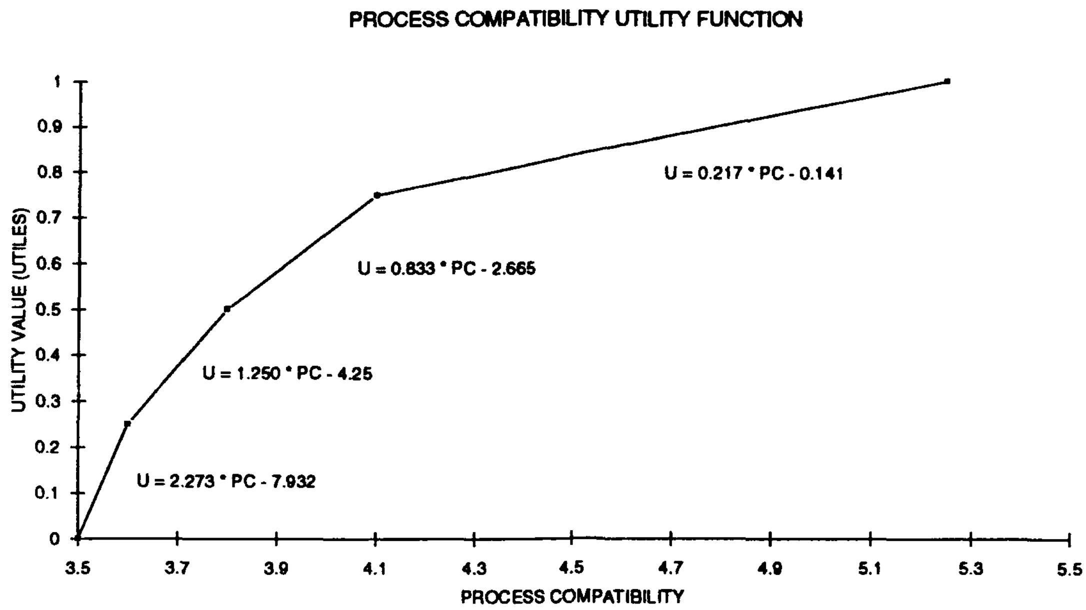
MAUT UNIVARIATE UTILITY FUNCTIONS

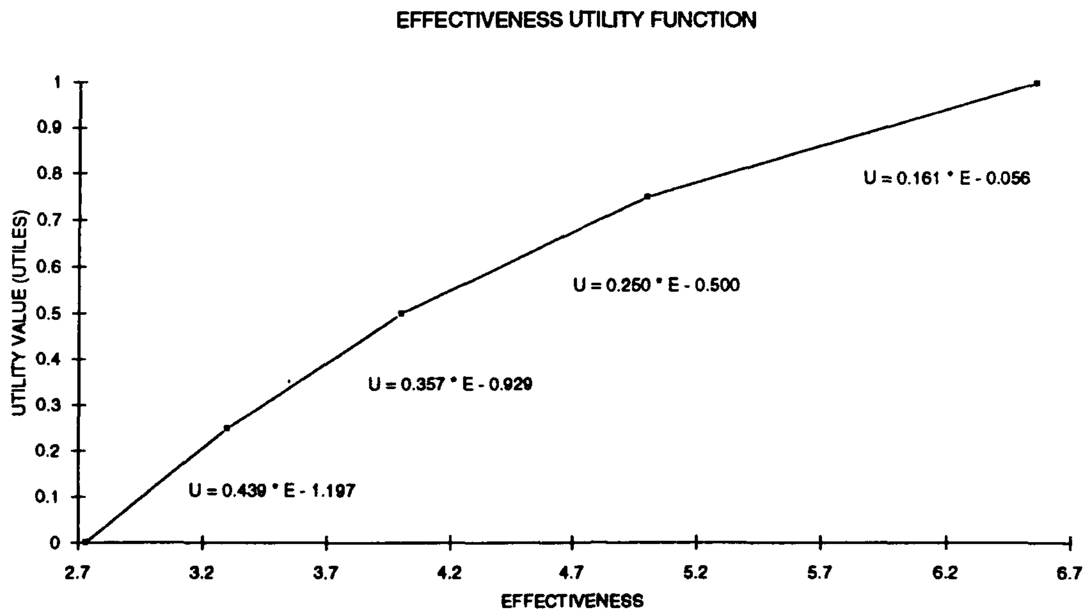
ENVIRONMENTAL IMPACT UTILITY FUNCTION

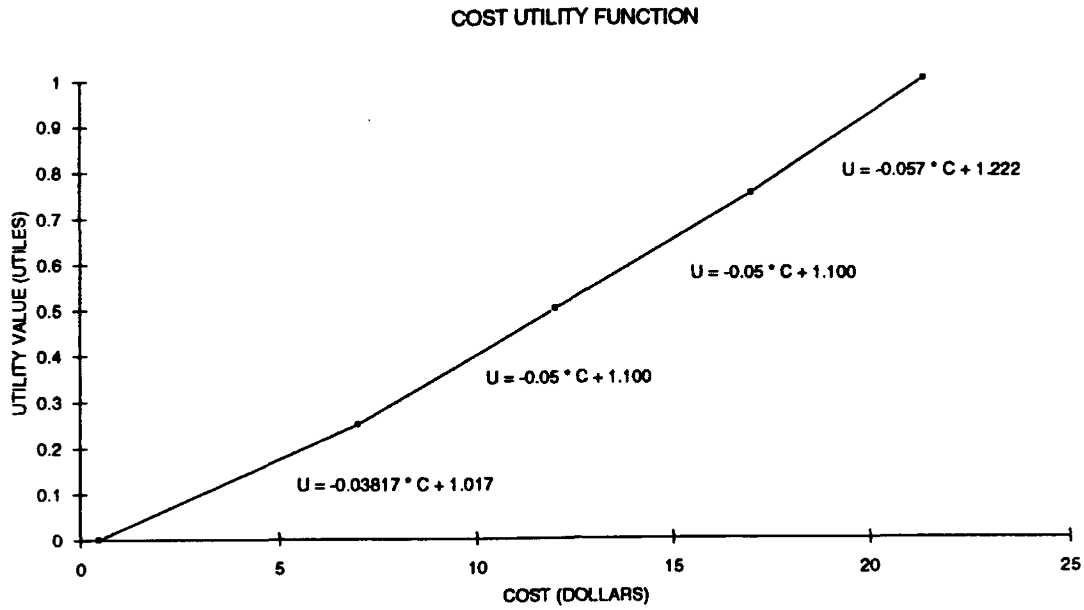


HEALTH/SAFETY IMPACT UTILITY FUNCTION




PROCESS COMPATIBILITY UTILITY FUNCTION
UTILITY VALUE (UTILES)
PROCESS COMPATIBILITY
U = 0.217 * PC - 0.141
U = 0.833 * PC - 2.665
U = 1.250 * PC - 4.25
U = 2.273 * PC - 7.932
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
3.5
3.7
3.9
4.1
4.3
4.5
4.7
4.9
5.1
5.3
5.5


EFFECTIVENESS UTILITY FUNCTION
UTILITY VALUE (UTILES)
EFFECTIVENESS
U = 0.161 * E - 0.056
U = 0.250 * E - 0.500
U = 0.357 * E - 0.929
U = 0.439 * E - 1.197
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
2.7
3.2
3.7
4.2
4.7
5.2
5.7
6.2
6.7


COST UTILITY FUNCTION
UTILITY VALUE (UTILES)
COST (DOLLARS)
U = -0.057 * C + 1.222
U = -0.05 * C + 1.100
U = -0.05 * C + 1.100
U = -0.03817 * C + 1.017
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
5
10
15
20
25

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Vita

Jaimie S. Tiley was born on 10 January 1964 in Piqua Ohio. He graduated from Wright State University in 1987 with a Bachelor of Science in Engineering (Specialty: Systems Engineering). Upon graduation, he began working for the United States Air Force, Aeronautical Systems Command (ASC) at Wright-Patterson AFB. Assigned to the Aeronautical Equipment System Program Office (SPO) as an Acquisition Management Engineer, he managed various technology insertion programs. Responsibilities included chairing a computer support team whose tasks included computer and network support, software/information system development and computer training.

He graduated in 1991 with a Masters of Science in Engineering (Specialty: Systems Engineering) from Wright State University. Upon graduating, he was designated the Environment Manager for the ASC/AEM division, responsible for environmental compliance and management efforts in connection with all acquisition programs. In February 1992, he was reassigned to the Environmental Management office at ASC where he was collocated to the Subsystems SPO as an environmental engineer. He became a Professional Engineer (Ohio) in March 1993 in the field of mechanical engineering. In May 1993, he was chosen to attend the Air Force Institute of Technology.

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This study developed a multicriteria decision making methodology for the ranking of solvent cleaning process alternatives. This includes development of univariate value functions and criteria and the incorporation or required alternative attributes. It also compares the Analytical Hierarchical Process and Multiattribute Utility Theory in reference to a cleaning substitution process. An actual Air Force cleaning process evaluation problem is considered to verify the research. The test problem ranks several cleaning alternatives for the replacement of a hazardous solvent used in the general cleaning of aircraft engine components.

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